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# Economic Geology

and the

Bulletin of the Society of Economic Geologists

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## CONTENTS

Regional Structural Features of the Yellowknife Area ..... *Neil Campbell* 687

Shallow, High-temperature Pegmatities, Grant County, New Mexico ..... *V. C. Kelley and O. T. Branson* 699

Ore Deposits and Geologic Age ..... *Stanko Miholić* 713

Mineral Deposits of Magmatic Origin ..... *Djalma Guimaraes* 721

Report Committee on Basic Research in the Field of Industrial Minerals and Rocks, S. E. G. ..... *Joseph L. Gillson and Richard H. Jahns* 737

*Reviews:*

Origin and Development of Craters (Jaggar) ..... *M. L. Mignone* 747

Memorandum sobre los Problemas de la Industria Minera de Bolivia (Aramayo) ..... *M. L. Mignone* 748

When the Oil Wells Run Dry (Fuchs) ..... 748

Colloid Science, A Symposium (Rideal and Others) ..... 749

Books Received ..... *Alan T. Broderick* 749

*Scientific Notes and News* ..... 753

*Index, Volume XLII* ..... 755

*Contents, Volume XLII* ..... i

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ECONOMIC GEOLOGY

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VOL. XLII DECEMBER, 1947 No. 8

# REGIONAL STRUCTURAL FEATURES OF THE YELLOWKNIFE AREA.

NEIL CAMPBELL.

ABSTRACT.

In the Yellowknife area, the sequence of geological events in Archean times began with extensive outpouring of volcanic flows, followed by intermittent vulcanism and sedimentation, and finally by sedimentation with little or no vulcanism. These rocks were subjected to granitic intrusion and folding accompanied by thrust faults which are now recognizable as mineralized shear zones. A later granitic intrusion and crustal disturbance cross-folded earlier structures and probably produced new ore bearing structures. The final phase in the structural development was the intrusion of diabase dikes followed by major strike-slip faults which cut all pre-existing rocks and known mineralization.

## INTRODUCTION.

THE area under consideration in this paper is confined mainly to the immediate vicinity of Yellowknife Bay, which is situated on the north arm of Great Slave Lake, N. W. T., at approximately latitude 62°–25′ N. and longitude 114°–20′ W. Within this area are found most of the structural conditions which, with slight local modifications, affect the surrounding country over an area of many thousands of square miles.

Records of geological observations in the Yellowknife area date back to the early explorers, but it was not until 1935 that systematic mapping was started by the Geological Survey of Canada under the field direction of A. W. Jolliffe. Since that time, much detailed information has been gathered, not only by the Geological Survey, but by the geologists of Consolidated Mining and Smelting Co. and other private organizations.

High tribute must be paid to the painstaking and thorough work of Dr. Jolliffe, whose maps and reports have been freely drawn upon for the purpose of this paper. The writer also takes pleasure in acknowledging many stimulating discussions with Survey geologists Dr. J. F. Henderson and Dr. C. S. Lord, with his colleagues in the Yellowknife field, including Mr. N. H. C. Fraser, Dr. J. D. Bateman and Dr. A. S. Dadson, and with the Chief Geolo-

gist of Consolidated Mining and Smelting Co., Dr. C. O. Swanson. Much of the data used here were obtained by Consolidated Mining and Smelting Co. by whose kind permission this paper is published.

## GENERAL GEOLOGY.

Roughly two-thirds of the Yellowknife Bay area is underlain by granitic rocks intrusive into the sediments, volcanics and other intrusives of the Yellowknife Group. For descriptive purposes it is convenient to divide the Yellowknife Group into three component members which are classified more on a petrological than a structural basis.

The basal member, which is best represented in the area along the west shore of Yellowknife Bay, consists dominantly of lavas and other rocks genetically related to the flows. Changes in the composition and primary structures within the flows are rarely sufficiently distinctive to permit their use as reliable structural markers. The larger proportion of the flows, particularly in the stratigraphically lower part of the series, is from black to dark green colored and basic to intermediate in composition. They are characterized by widespread, well-defined pillow structures although flows which are partially or entirely amygdular, variolitic or massive are also found in many places. Some flows are found to be thickly lenticular in section, but in general they tend to form roughly tabular bodies from 10 to 500 feet in thickness, and up to several thousand feet in lateral extent. Boundaries between flows are commonly marked by nothing more distinctive than chilled margins and/or changes in the primary structures in adjacent members. In some places, however, flow contacts are marked by irregularly-shaped beds of flow breccia or beds of chert and tuff.

Towards the top of the lower Yellowknife series, the flows become lighter colored and more acidic in composition. Abundantly pillowed flows give way to more massive types and clastic material in the form of flow breccia, tuff and agglomerate becomes more common.

Although much of the middle Yellowknife series is concealed beneath Yellowknife Bay, it is exposed in some places along the west shore of the bay and also to the east of the bay, notably around Duck Lake. This series consists of interbedded volcanic and sedimentary rocks, and in the western part of the area, its base is marked by a granite-pebble-bearing conglomerate and an angular unconformity indicating an interval or erosion. In the eastern part of the area, the basal conglomerate has been found on the south shore of Duck Lake only; elsewhere the flows of the lower formation appear to pass into the interbedded flows and sediments of the middle Yellowknife series without any apparent structural discontinuity. The flows of the middle Yellowknife series are mainly light-colored and are generally acidic in composition. The sedimentary phases are composed of conglomerate, arkosic grit, argillite and tuff. They are characterized by considerable variation in composition, both along and across individual beds, and by the common occurrence of well-defined cross-bedding.

The interbedded flows and sediments of the middle Yellowknife series are followed without any apparent structural break by a great thickness of sedi-

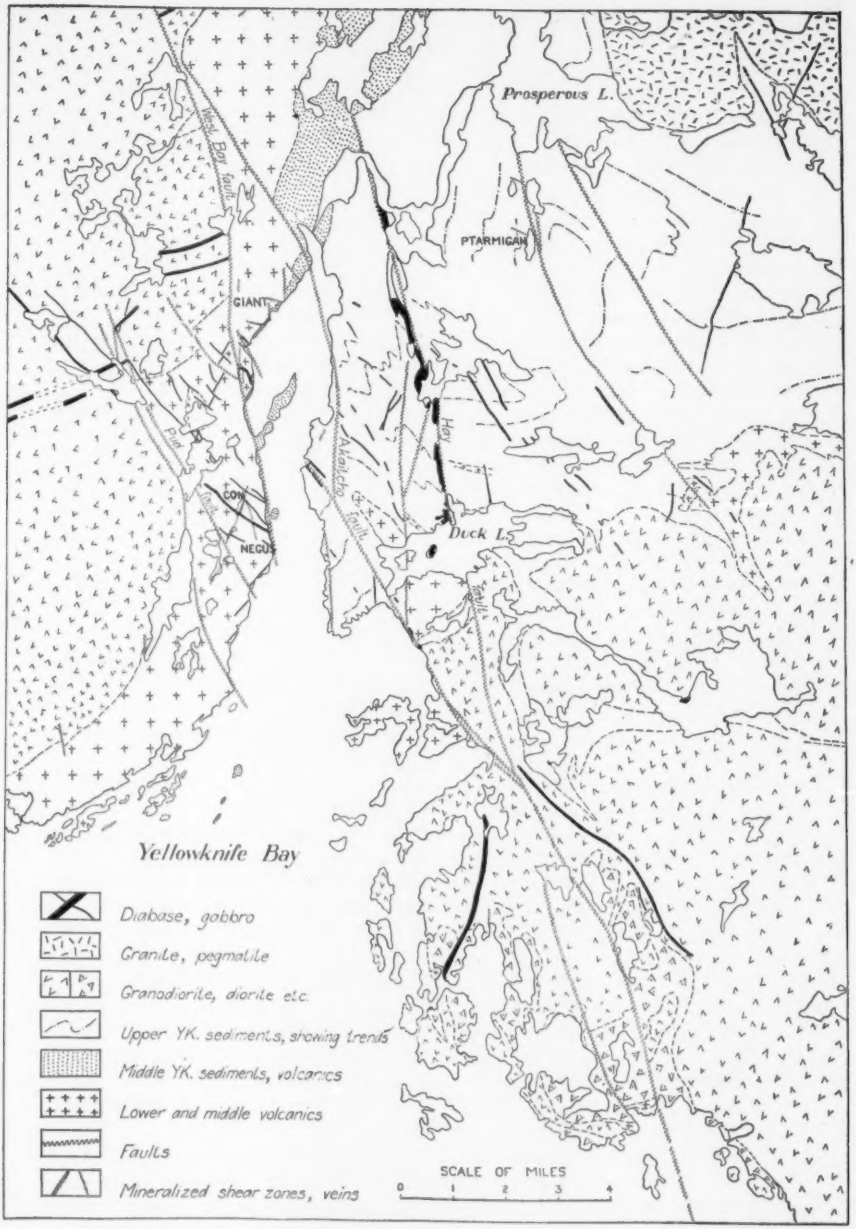


FIG. 1. Geology of Yellowknife Bay Area, N. W. T. Adapted from Geological Survey of Canada maps.

ments comprising the upper Yellowknife series. In the areas of least-pronounced metamorphism, these rocks are composed of graywacke and argillite but closer to the contacts of granitic intrusives, the sediments are altered to quartz-mica schists, slates and phyllite. Still closer to the granite, metacrysts of chiastolite, staurolite, garnet, etc. are found in great abundance. The sediments for the most part are well-bedded and are characterized by grain gradation from coarse at the bottom to fine at the top of individual beds.

Many dikes and sills intrude the Yellowknife group, being particularly abundant in the basal member. The earliest of these intrusives are sills, varying in composition from diorite to gabbro, and which in many places appear to have been injected along sedimentary horizons between flows. They range from a few feet to several hundred feet in thickness and from a few hundred feet to several miles in lateral extent.

The sills are cut by a series of intrusives known locally as the "early basic dikes." These dikes become progressively less common in the middle and upper Yellowknife series, but in parts of the lower Yellowknife series they are so numerous that they comprise from 10 to 20 per cent of the exposed rock. These dikes have been tentatively classified[1] into four main groups on the basis of mineralogical composition and relative age relationships. Most of the dikes are similar in composition to the lavas in which they lie, but they differ from the flows in that they generally have ophitic texture and commonly contain feldspar phenocrysts. A few of the dikes may have been feeders to the sills, but whether they played any part in the extrusion of the flows is not clear. The general trend of the early basic dikes in the lower Yellowknife series is north to northwesterly and they dip most commonly in a westerly direction. They appear to have been subject to most, if not all, of the folding and other structural deformation which affected the Yellowknife group as a whole.

The Yellowknife group is cut by parts of three large bodies of granitic rocks. One of these, lying northwest of Yellowknife Bay, is composed largely of biotite granodiorite, and shows transgressive intrusive contacts with the lower Yellowknife series in this area. Although its margins are sharply defined in most places, hornblendic inclusions are found within the granodiorite and numerous granitic dikes and a few small outlying stocks cut the flows near the contact. A second large granitic body lies southeast of Yellowknife Bay where it invades sediments of the upper Yellowknife series and a few small masses of volcanics. Its contacts are generally concordant with the bedding of the invaded rocks. The eastern part of this body may be classified as a biotite granodiorite and carries relatively few inclusions of foreign material. Its western portion is composed of biotite granodiorite and hornblende granodiorite. Within its boundaries are found numerous inclusions of sediments and volcanics showing varying degrees of assimilation or replacement by the host rock.

A third granitic body, lying about 6 miles northeast of Yellowknife Bay, also cuts sediments of the upper Yellowknife series. It consists of approximately equal proportions of muscovite-biotite granite and muscovite-tourmaline

[1] Campbell, N., unpublished MS, Massachusetts Institute of Technology, 1943.

pegmatite. Numerous pegmatitic dikes and other apophyses cut the sediments in the vicinity of its contacts.

The distinct similarity in general characteristics existing between the northwestern and southeastern granitic bodies suggests that they may be related in time and structural implications. On the other hand, there appears to be considerable justification for the belief that the northwestern, pegmatite-bearing granite is younger than either of the other two.

The youngest consolidated rocks in the Yellowknife Bay area are reddish-brown-weathering diabase dikes composed of relatively fresh plagioclase and pyroxene with minor amounts of olivine and opaque minerals. Quartz occurs as an accessory mineral in some places. These dikes vary from less than one inch to 350 feet in thickness. There would appear to be two systems or classes of late diabase dikes: those having a northwesterly trend and others having a northeasterly trend. There are three notable exceptions to this pattern, two of which consist of relatively thick, sub-parallel dikes which have been traced in an east-northeasterly direction for about 50 miles. The third body of diabase which does not conform to the general pattern is a flatly-dipping sheet striking in a northerly direction and lying along the west side of the Bay Fault.

## STRUCTURE.

The foregoing, highly generalized description of the various rock types found in the Yellowknife Bay area is based largely on direct observation and is reliable to the extent that the original observations are accurate. An analysis of the structural aspects of the geology, on the other hand, calls for considerable interpretation of observed geological phenomena and, since the structure is very complex, it is possible that alternative explanations of certain structural details may be obtained.

The earliest event in the geological history of the area for which there is any direct evidence is the extrusion of the basic flows of the lower Yellowknife series. The general absence of erosion surfaces and the scarcity of clastic material between the earlier flows suggest that they may have been deposited in comparatively rapid succession. Attention has been drawn [2] to certain similarities between these flows and the more recent flood basalts of Deccan and the Atlantic petrogenic province. Toward the end of the lower Yellowknife period, the flows were becoming more acid in composition and volcanic ash and possibly erosional detritus began to be deposited in increasing quantities. Meanwhile, earlier flows which were already solidified were being invaded by many sills and dikes. It would appear that the intrusion of the so-called early basic dikes and sills overlapped in time the entire Yellowknife group and possibly even the intrusion of granite. As has been pointed out, there is very little evidence suggesting that the early dikes acted as feeders to the flows. On the contrary, the fact that they show a marked similarity in direction of strike in the lower Yellowknife series where they are most common, suggests that they may have resulted partly from stresses of regional extent, existing in the rocks at this very early time.

[2] Newhouse, W. H.: Personal communication.

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The lower Yellowknife period was brought to a close by a minor tectonic disturbance. Possibly in the westerly or northwesterly part of the area, an uplift or tilting occurred in which a land mass, subject to the forces of erosion, was developed while in the easterly part of the area, sedimentation was taking place. Not only were the lower Yellowknife volcanics exposed by this movement but also pre-existing members of the basement complex, remnants of which are found as pebbles in the basal conglomerate of the middle Yellowknife series. The presence of granitic pebbles here suggests the existence of intrusives which may antedate the volcanics.

The change in conditions brought about by the uplift does not appear to have halted active vulcanism, although the flows became more acidic in composition. Possibly their extrusion on land surfaces undergoing erosion provided some detrital material for the arkosic sediments now found in the middle Yellowknife series. In marine areas, the extrusion of lavas continued intermittently with the deposition of clastic and pyroclastic material. The intrusion of dikes and sills also continued throughout this period and long after vulcanism had ceased. They are fewer in number in the middle Yellowknife series, however, and in the upper Yellowknife series they are rather uncommon.

Although the geological conditions prevailing when the middle Yellowknife sediments and flows were laid down must have differed considerably from those in the period of upper Yellowknife sedimentation, the change appears to have been transitional and unmarked by any structural discordance. In the upper Yellowknife period, volcanic activity appears to have been generally absent. Great quantities of detrital material ranging in composition and texture from sand to silt, but containing few, if any, coarse fragments, were deposited in a monotonous succession of more or less well-defined beds. These beds now range in thickness from a fraction of an inch to 20 or 30 feet and average between one and three feet. The most characteristic feature of most of these beds is the grain gradation which, from comparison with other much less common primary structures such as scour and cross-bedding, appears to be from coarse at the bottom to fine at the top in almost all places. The nature of the cyclical geological conditions which could have produced a great succession of beds having these characteristics poses a problem which has never been explained satisfactorily.

Subsequent erosion has removed all trace of any sedimentary or volcanic rocks which may have followed the deposition of the upper sediments in the Yellowknife Bay area. The next event of which there is any apparent record is a period of mountain building and granitic intrusion. The results of this great upheaval are somewhat confused by more recent structural developments, but because of the important part it is believed to have played in the formation of gold deposits, it deserves the closest scrutiny.

Most of the Yellowknife group appears to have been folded into a large asymmetric syncline with a subsidiary anticline on its southeastern limb. The axis of the syncline, now distorted and dislocated by later cross-folding and faulting, follows a northeasterly plunging course up Yellowknife Bay. The exposed rocks on the northwesterly limb consist largely of volcanics of the

lower Yellowknife series and have tops facing southeast. Small variations in the strike and dip of these flows indicate gentle monoclinal folding but little evidence of normal drag-folding is found. In some of the few places where the middle Yellowknife series is found on the west limb of the syncline, the beds are overturned—a condition which may reflect the angular unconformity between the middle and lower series.

The exposed rocks on the southeast limb of the syncline and subsidiary anticline consist mainly of sediments and flows of the middle and upper Yellowknife series. In most places on the southeasterly limb of the syncline and the westerly limb of the subsidiary anticline, the beds are overturned, indicating that the axial planes dip southeasterly. It seems probable that the overturned aspect of the structure is related to this earliest period of folding.

It is significant that the axis of the syncline lies roughly midway between the large northwestern and southeastern bodies of granodiorite which, as stated previously, are believed to be related in origin. The relative positions of these two intrusive bodies suggest that the direction of their advance into the pre-existing rocks is related to the direction of folding. The exact time relations between the folding and the intrusion of the early granodiorite cannot be determined with any degree of certainty, but the broad facts of the case do suggest that, at about this time, direct compressive stresses of regional extent existed in a gently plunging northwesterly direction. In places other than directly between the two granitic bodies, the direction of applied stress probably differed in direction and other characteristics and this is reflected in the diverse trends found in the Yellowknife group elsewhere.

It has been pointed out that the lower Yellowknife volcanics, which dominate the northwest limb of the syncline, have poorly developed bedding and are relatively massive as compared to the well-bedded sediments of the upper Yellowknife series which form the greater part of the southeast limb. It might be concluded from this that of the two, the volcanics are the more competent rocks—a line of reasoning that seems to be supported by other observations. As the folding progressed, the sedimentary rocks probably yielded through plastic deformation accompanied by the development of many intricate minor folds. In the more competent volcanic rocks, on the other hand, relief from stress probably came about to a lesser extent through plastic deformation and more through the development of numerous faults or shear zones. Most of these shear zones would appear to fall into a rude pattern consisting of a major system striking in a general northeasterly direction and a minor system of considerable weaker shear zones striking from north to northwest. The dip in most shear zones of both systems is westerly and where the direction of movement has been determined, it is dominantly vertical, the westerly side moving up and south relative to the easterly side. Shear number 4 on the Con property is one of the more important members in this pattern, but there are many others throughout the volcanic rocks west of Yellowknife Bay. In the sediments east of the Bay, the fault containing the Shaft Vein of the Rich property may be the only well-known example.

It would appear that the shear zones are closely related in time to the intrusion of the granodiorite. In some places shear zones extend into small

outlying bodies of granodiorite but they generally become weaker and disappear a short distance from the contact. In other places the injection of granitic dikes appears to have been controlled by the shear zones and ore mineralization which later appeared in the shear zones also penetrated the granitic material.

To recapitulate, it would appear that the first major structural disturbance in the Yellowknife Bay area was brought about by direct compressive stresses in a northwest-southeast direction, resulting in a northeasterly trending syncline. The lateral advance of the early northwestern and southeastern bodies of granodiorite may have roughly paralleled the direction of applied stress. The final stages of deformation appear to have been accompanied by subsidiary folding in the incompetent rocks on the southeast and the development of thrust faults or shear zones in the relatively competent rocks on the northwest.

The next major structural event of which a record remains was the intrusion of the younger granite body northeast of Yellowknife Bay and the development of compressive stresses acting in a southwesterly direction. As a result of the preceding period of folding, the sediments of the upper Yellowknife series had a northeasterly trend and steep dips. The new southeasterly compressive stresses, applied in approximately the same direction as the strike of the sediments, appear to have buckled the beds into an intricate series of steeply plunging cross folds with axial planes normal to the direction of application of the stresses. The resulting pattern of folding is complex in the extreme, particularly in the northeastern part of the Yellowknife Bay area. Toward the southwest the effect of the disturbance is less pronounced, and in the volcanic rocks west of Yellowknife Bay there are no structures which are already attributable to this period of folding and intrusion.

Although the rocks mainly affected by the intrusion of the younger granite and accompanying folding are the relatively incompetent sediments of the upper Yellowknife series, some structure analogous to the early shear zones might be sought. No obviously close parallels can be drawn, but it is possible that the gold-quartz veins of the Ptarmigan and other properties are related to the younger, northeastern granite in somewhat the same way as the shear zones of the Con and neighboring properties are related to the earlier southwestern granite.

The final phase in the structural development of the Yellowknife Bay area was the intrusion of numerous diabase dikes followed by faulting on a tremendous scale. These two events are treated together because they are believed to be related in origin and because the geological conditions to which they owe their existence were totally different from conditions which produced earlier structural changes.

The so-called "late diabase" is evidently younger than all other consolidated rocks in the area. With a single doubtful exception, all observations clearly indicate that the diabase is also younger than the early shear zones and the mineralization they contain. These intrusives form a diamond-shaped pattern of dikes, one system of which trends northwesterly and the other in a northeasterly direction. From the scant data available, it would

appear that the northwesterly striking dikes dip steeply northeast and the northeasterly trending dikes most commonly dip steeply southeast. The few dikes which do not conform to this general pattern have already been described.

It has been stated [3] that the late faults in the Yellowknife Bay area rank among the largest known steeply-dipping dislocations in the earth's crust. These faults may be classified into three closely related systems. One system, which includes the West Bay fault, has a north-northwesterly trend and has been traced for approximately 70 miles beyond the Yellowknife Bay area. The second system, which in a broad sense may be structurally identical with the first, has a northerly trend and has been traced for 50 miles up the Yellowknife River. The third system, which trends slightly south of west is of comparative insignificance in the Yellowknife Bay area, but is mentioned here as representing groups of faults of considerable magnitude beyond the immediate vicinity of Yellowknife Bay.

All three systems have characteristics of such similarity that they are believed to be closely related in time and origin. Where it has been possible to determine their dips accurately through diamond drilling, they have been found to stand within about 5 degrees or less of vertical. Such slip determinations as have been made show that most, if not all, of the movement has occurred subsequent to the intrusion of the youngest of the late diabase dikes. The nature of the fracturing and the type of mineralization and wall-rock alteration associated with various late faults are similar. These characteristics are sufficiently distinctive to make it possible to differentiate between pre-diabase shears and faults and post-diabase faults in many places where more direct evidence is not available.

Most of the movement along the post-diabase faults appears to have taken place along remarkably narrow fractures filled mainly with clay-like gouge and small angular-fragments of the host-rock. A section of the West Bay Fault showing more than 3 miles of movement has been cut by several diamond drill holes and it has been found that the gouge-breccia zone varied from a few inches to a few feet in width. Even at one point on the Giant property where there is a sharp change in the strike of the fault, the movement does not appear to have produced a wide zone of shearing although the rock embraced by the obtuse angle of the deflection is cut by multiple minor subsidiary faults.[4] The wall rocks adjacent to the late faults are generally fractured and mylonitized, but wide zones of schistose foliation definitely attributable to shearing of the host-rock by post-diabase faults are rare.

Considered in relation to their magnitude, the faults are generally accompanied by remarkably little mineralization and hydrothermal alteration of the wall-rocks. In some places, however, milky or cherty quartz occurs as veins in the faults or as stockworks in the fractured zones along the walls of the faults. Many such veins carry fragments of country-rock, showing varying degrees of replacement by the quartz. Amethystine quartz has been found, notably in the Pud Lake fault. Among the metallic minerals,

[3] Jolliffe, A. W.: Geol. Survey Can., Map 709–A.

[4] Bateman, J. D.: Personal communication.

pyrite and (more rarely) chalcopyrite occur in small quantities. Hematite and specularite are found in almost all late faults both in the principal fractures and brecciated wall-rocks. Quartz and calcite comb structures are found in many faults, commonly along water-courses, which would suggest deposition from circulating ground waters. Where faults are found in the vicinity of heavily-mineralized pre-diabase shear zones, skeletal crystals of galena and botryoidal masses of marcasite are found in open cavities. These are probably the result of solution and redeposition. Gold is also reported in commercially insignificant quantities.[5]

In addition to the introduction of quartz and hematite, chloritization appears to be the chief form of wall-rock alteration and it is confined to within a comparatively short distance of the locus of movement. Completely chloritized fragments within the fractured zone commonly remain as discrete particles with direction of foliation unrelated to that in adjacent fragments.

In contrast with the late faults, the pre-diabase shears are marked by relatively wide bands of chlorite schist containing no well-defined breaks along which most of the movement has occurred. Fracturing and mylonitization of the wall-rocks rarely occur although brecciation is found in many places within shear zones where silicification of the schist and recurrent movement have taken place. The schist zones pass more or less transitionally into the massive country-rock which rarely shows appreciable wall-rock alteration. The mineralization found within the shears in many places is characteristic of Yellowknife gold ores and this, together with the general absence of primary iron oxides, also serves to distinguish the pre-diabase shear zones from the post-mineral faults. The reasons for the marked mineralogical and structural differences between the pre-diabase and post-diabase faults is a problem requiring further study and will not be considered here.

The mapping of the Geological Survey has shown that displacements along individual members of the northerly trending systems of late faults range up to about 5 miles and the cumulative movement on all faults in a belt 10 miles wide totals about 11 miles. In most places the direction of movement is dominantly horizontal, the easterly side moving north with respect to the westerly side. Since almost all structural markers cut by the faults are steeply dipping, it is difficult to determine the amount and direction of the horizontal components of movement. Recently however, the Consolidated Mining and Smelting Co. undertook to determine as accurately as possible the amount and direction of movement on that part of the West Bay fault which lies along the west shore of Yellowknife Bay. The results of this investigation indicate that the west side moved slightly more than 1,000 feet down and 16,000 feet south, relative to the east side. Investigation of the Pud Lake fault where the horizontal component of movement is 1,200 feet shows that there too the vertical component of movement is very small.

The Akaitcho fault might appear to provide an exception to the general rule that displacements along the major faults are mainly horizontal in direction. It has been reported that the displacement along the Akaitcho

[5] Jolliffe, A. W.: "Yellowknife Faults and Orebodies," The Precambrian, May 1945.

fault may be 2 miles south and ½ mile upward on the west side with respect to the east side. The calculation involves the use as a structural marker of a shallow-dipping diabase sheet which must be projected beneath drift and water covered areas for more than a mile in order to determine where the diabase is cut by the fault on both the east and west sides. Another, equally plausible solution could be obtained if the sheet were projected beneath a drift-covered belt at a different location. In this case the ratio of horizontal to vertical movement would be very close to that found in the West Bay fault. From information available at present, it is concluded that movement along the major post-diabase faults in the Yellowknife Bay area is generally mainly horizontal in direction.

The third system of late faults has a westerly trend and steep to vertical dips. Faults of this system are much less common than the former, and the displacements are measured in tens or hundreds of feet rather than in thousands of feet or miles. With a few exceptions, movement of the north side has been eastward relative to the south side. Little is known about the vertical components of movement, but it is believed that they are small in comparison to the horizontal components.

Although the intrusion of the late diabase dikes preceded most, if not all, of the movement of the late faults, their origin may represent successive stages in the development of a single major structural condition which culminated in the faulting. This concept receives indirect support from several geological considerations. The diamond-shaped pattern formed by the late diabase dikes is not confined to the Yellowknife Bay area, but with slight modifications in orientation, occurs in many places over an area of many thousands of square miles and in almost every type of host-rock. Major faults having about the same orientation as those at Yellowknife are also found at many places over the same large area. Hence the stress conditions which were presumably relieved by the late diabase dikes and those which were relieved by the faults were co-extensive, and were fairly consistent in their respective orientations throughout the area. More direct evidence of the close association of the intrusion of diabase and faulting is seen in a few places—notably at Hay Lake, where a fault is mapped as following the course of an intrusive. Elsewhere, along the west side of the West Bay fault, a few northwesterly-trending dikes swing in a southerly direction in the immediate vicinity of the fault. This suggests that even during the intrusion of the dikes, highly localized stress conditions had already developed along the locus of the fault, resulting in local deviation in the general direction of tension.

If it be assumed that the intrusion of the late diabase dikes represents the relief of tensional stresses, it is difficult to explain the widespread occurrence of a diamond-shaped pattern formed by the dikes which are presumably of approximately the same age. It will be noted that the northwesterly trending system approximates in strike the direction of the tensional component of stresses which could have produced the late faults, but no such simple explanation can be found for the northwesterly dikes.

Consideration of the great forces which produced the late faults and possibly also contributed to the development of the diabase dikes carries us well into the uncertain field of speculation, but because a comparison of these forces with the forces which developed the early mineralized shear zones is of considerable economic importance, a few comments should be made here. It is believed that the pre-mineral shear zones resulted mainly from direct compressive stresses which were accompanied by folding and granitic intrusion. Presumably ore bearing solutions occurred in both periods of granitic intrusion. Ore bodies were developed wherever the presence of abundant, suitable ore bearing solutions coincided in both space and time with favorable local structural conditions. The stresses which developed the pre-diabase shears must be considered local in their space distribution and probably changed considerably in character, direction and intensity within distances of only a few miles.

On the other hand, the stress which culminated in the late faults does not appear to be related in any way to regional folding or the intrusion of granite. As a corollary to this statement, it might be added that probably few, if any, substantial quantities or ore bearing solutions were present at the time when the late faults occurred. Possibly, in its initial stage, the stress was relieved by the development of tension fractures into which the late diabase was injected and, as it continued to mount, the rocks yielded along great faults. The fact that both diabase dikes and faults retain their orientation to a remarkable degree over such a large area suggests that the stress had a fairly constant direction of application—a concept which has strong implications in the general theory of homogeneity of stress within the earth's crust. It is suggested that, in broad terms, the stress was rotational in character in contrast to the generally tangential nature of the stresses which developed the pre-diabase shear zones.

In conclusion, it might be said that the rocks of the Yellowknife Bay area illustrate a structural history of extreme complexity. In the early stages, we find an orderly sequence of vulcanism, sedimentation and at least one period of erosion. The first of a succession of cataclysmic events came with the intrusion of granitic rocks, regional folding and the development of mineralized shear zones. Later, a second intrusion of granitic rocks, accompanied by a new set of stresses, cross-folded earlier structures and developed new ore bearing structures. The final event was the development of tremendous widespread stresses which resulted in the major faults of the Yellowknife Bay area.

EXPLORATION OFFICE,
CONSOLIDATED MINING AND SMELTING CO.,
YELLOWKNIFE, N. W. T., CANADA,
*Sept. 20, 1947.*

# SHALLOW, HIGH-TEMPERATURE PEGMATITES, GRANT COUNTY, NEW MEXICO

V. C. KELLEY AND O. T. BRANSON.

CONTENTS.


| | PAGE |
|---|---|
| Abstract | 699 |
| Introduction | 699 |
| Geology | 701 |
| General | 701 |
| Volcanic rocks | 701 |
| Rhyolite porphyry | 702 |
| Moonstone deposits | 703 |
| Pegmatite | 703 |
| Mineralogy | 704 |
| Quartz | 704 |
| Sanidine | 705 |
| Accessory minerals | 706 |
| Paragenesis | 706 |
| Origin | 706 |
| Rabb Canyon deposits | 706 |
| Review of theories of origin | 708 |
| Classification | 709 |
| Early formation | 710 |
| Temperature | 711 |
| Geologic age | 712 |
| Conclusions | 712 |



ABSTRACT.

Shallow-seated, high-temperature sanidine pegmatites of Tertiary age occur in the Black Range, Grant County, New Mexico. The pegmatites are small bodies within a rhyolite porphyry plug that has been injected into rhyolite tuffs of Tertiary age. The pegmatites consist dominantly of quartz and sanidine with accessory quantities of cleavelandite, biotite, sphene, magnetite, and ilmenite. The sanidine, which occurs in crystals up to one or two feet on a side, is the moonstone variety and displays limpid blue and white play of colors. Microcline is absent, and on the basis of the sanidine the pegmatites are believed to have crystallized at temperatures higher than those of the normal plutonic pegmatites. Textural and structural evidence indicates that the pegmatites crystallized prior to the enclosing rhyolite porphyry. The origin and classification of pegmatites are reviewed.


## INTRODUCTION.

THE sanidine pegmatites described in this paper are located in the Gila National Forest along the west slope of the Black Range about 2½ miles

north of New Mexico Highway 180 near Noonday Canyon (Fig. 1). Noonday Canyon is 10 miles west of the crest of the Black Range at Emory Pass and about 12 miles from Mimbres by road. The mountains in this vicinity are rugged and thickly covered with piñon, pine, and other trees or brush common to the high areas of the southern part of the State. The locality is most easily reached by foot along Rabb Canyon. The altitude at the deposits is about 7,000 feet.

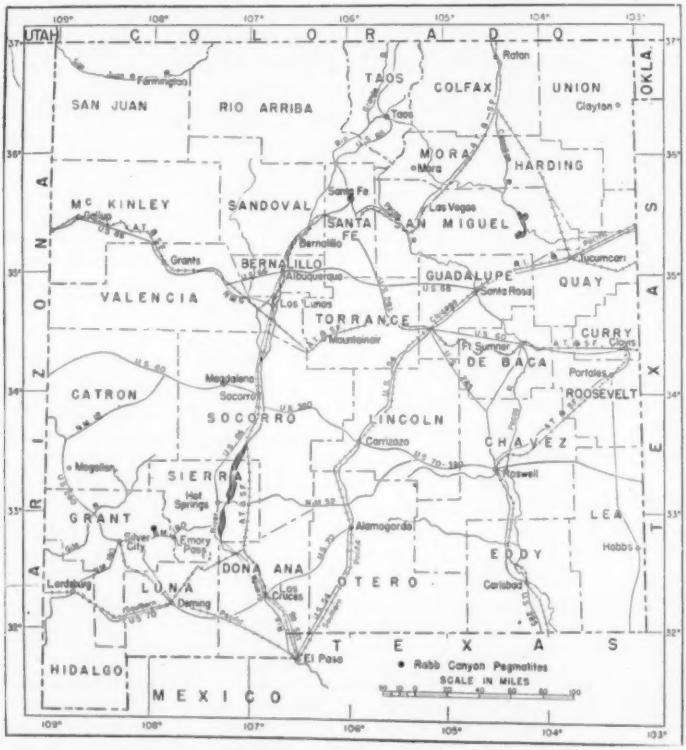


FIG. 1. Index map.

The deposits have been known for 20 to 25 years and have been worked and claimed occasionally by different individuals. The moonstone sanidine from Robb Canyon deposits is largely unsuitable for gem cutting, but much of this material has been sold by several of the large mineral companies as mineral specimens because of its beautiful play of colors. The output of gem material has been small.

The authors are grateful to S. A. Northrop, W. T. Schaller, and G. T. Faust who read and criticized the manuscript.

GEOLOGY.

*General.*—The Black Range lies in Sierra and Grant counties. Its length along a nearly north line is about 80 miles. The maximum width in the latitude of the moonstone sanidine deposits is about 15 miles. The range is largely composed of Tertiary volcanic rocks, but pre-Cambrian and Paleozoic rocks are exposed along part of the east slope and near the crest of the range. The range is described by Harley [1] as an arch which has been broken and tilted westward by a series of faults along the east side. The Tertiary

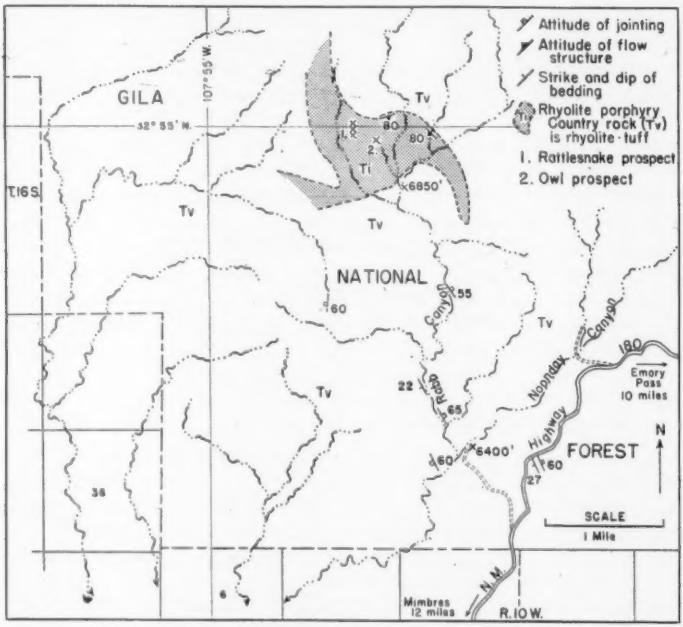


FIG. 2. General geologic map.

rocks consist of flows, breccias, tuffs, and intrusives ranging from andesite to rhyolite. They are estimated [2] to be as much as 3,000 feet thick and are probably early Tertiary in age. The andesitic rocks are generally the older.

*Volcanic Rocks.*—In the part of the range in which the moonstone deposits are located the volcanic rocks consist of rhyolite flows and rhyolite tuff, breccia, and flow breccia. The tuff predominates. The bedding is inclined westward 20°–30° (Fig. 2). The rock is highly and regularly jointed and expresses itself clearly on aerial photographs in a disposition similar to a

[1] Harley, G. T., The geology and ore deposits of Sierra County, N. M.: New Mexico School of Mines, State Bur. of Mines and Min. Res., Bull. 10, p. 62, 1934.

[2] Op. cit., p. 61.

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doubly plunging anticline. The moonstone pegmatites occur within an irregular intrusive of rhyolite porphyry (Fig. 2) which is probably also early Tertiary in age.

The rock immediately adjacent to the rhyolite porphyry is dense gray-brown tuff. Thin sections show the tuff to consist principally of fragments of sanidine, quartz, oligoclase, and biotite in a vitric matrix. Accessory quantities of sphene, magnetite, apatite, and green hornblende comprise the remaining constituents. Crystalline material makes up 60 percent; and vitric material, 40 percent of the rock. The proportions of the minerals comprising the crystalline material are as follows:

| | |
|---|---|
| sanidine | 40 percent |
| quartz | 25 percent |
| oligoclase | 15 percent |
| biotite | 15 percent |
| accessories | 5 percent |

Occasional crystal faces remain on the mineral fragments. The average diameter of the dominant-sized fragment is about one millimeter, but some sanidine fragments are as much as ten millimeters in diameter.

*Rhyolite Porphyry.*—The rhyolite porphyry is an irregular intrusive body with three principal curving extensions. The average diameter of the central part is about 4,000 feet. Flow banding, which is vertical to steeply inclined, is developed along the margins of the intrusive. The moonstone pegmatites occur as irregular segregations in the porphyry.

The great bulk of the intrusive is a light-gray porphyry with an earthy-gray groundmass which under the microscope is fine-grained to clouded submicroscopic in size. In the usual rock the most abundant phenocrysts have an average diameter of about one millimeter, but many phenocrysts are as much as five millimeters. The rock is mostly finely miarolitic and somewhat friable in surface outcrops or in the shallow cuts, making good thin-sections difficult to prepare. The minerals and their percent-composition are essentially the same as those of the tuff described above.

Locally, and especially in the vicinity of the pegmatites, the texture ranges greatly. There are, however, two distinct textures. One is a fine-grained, sugary-appearing porphyry consisting of about 80 percent nearly equidimensional phenocrysts of quartz and sanidine in a microcrystalline groundmass. The other is granitoid in which the average diameter of grain is about three millimeters with occasional grains of sanidine, oligoclase, or quartz as much as ten millimeters. Even in this fabric there is about ten percent microcrystalline groundmass. Texturally, although not always spacially, the granitoid material may be said to grade into the pegmatite. The pegmatite is described below under Moonstone Deposits.

Considerable areas of the intrusive are whitened as a result of hydrothermal alteration to sericite, kaolin, and pyrite; weathering of the latter has yielded light yellow-brown outcrops.

MOONSTONE DEPOSITS.

*Pegmatite.*

The pegmatite bodies that have been discovered and worked are in the northwest part of the intrusive. Others may be present elsewhere but the central and southeastern parts of the intrusive are poorly exposed. The pegmatites, which had been discovered and prospected up to 1945, consist of four small bodies on the Rattlesnake and Owl claims. Three of the bodies are on the Rattlesnake claim and one on the Owl claim (Fig. 2).

The southernmost prospect on the Rattlesnake claim is a trench about 15 feet long, 5 feet wide, and 6 feet deep opened on an irregular pegmatite whose long dimension strikes N. 65° W. Little or no pegmatite remains in the bottom or the southeast end of the trench. In the northwest end of the trench the pegmatite is three feet wide. The pegmatite contains numerous fine-grained granite inclusions. The pegmatite minerals consist dominantly of smoky quartz and sanidine, intergrown in anhedral and subhedral masses typical of pegmatites. The smoky quartz is dark, much shattered, and in masses or single crystals up to six inches in diameter. Sanidine is equal to quartz in

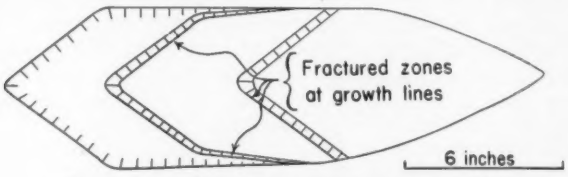


FIG. 3. Sketch of a large zoned quartz crystal.

abundance and those crystals that remain are as much as five inches in diameter. Biotite and cleavelandite are sparsely scattered through quartz and sanidine in plates up to two and a half inches in diameter and one-sixteenth inch in thickness. Considerable sanidine of good moonstone quality came from this deposit, and some moonstone pieces of commercial quality as much as four inches in diameter were obtained.

The middle prospect on the Rattlesnake claim is about 100 feet north of the south prospect. The trench and pegmatite trend about N. 70° W. In 1945 this deposit was being worked and the trench was about ten feet long, three feet wide, and four feet deep. Near the center of the trench the pegmatite is about three feet wide but tapers to less than one foot wide at either end of the trench. The composition and texture of the pegmatite are similar to that of the south deposit. Considerable granitoid material borders the pegmatite and occurs as inclusions within the pegmatite.

The north prospect on the Rattlesnake claim is about one hundred yards north of the middle prospect. It is a hillside cut driven N. 54° E. into the hill for 21 feet, the cut being about 8 feet deep at the back end. The pegmatite is irregular and spotted in fine-grained granite. The sanidine is mostly white and not of moonstone quality. Large quartz crystals are the most striking feature of this deposit. They range in color from white to light

smoky. The crystals are subhedral and euhedral and range from 3 to 15 inches in diameter and from 8 to 24 inches in length. The subhedral crystals enlarge from pointed bases through one or two well-marked growth lines to rough terminations (Fig. 3). The growth lines consist of highly fractured layers, about ten millimeters wide, which are identical to the outside of the crystals. Many of these crystals are weathered out on the hillside south of the cut. They are commonly broken apart on the growth layers and therefore have rough molds in the base of the part that crystallized earlier.

The largest of the small pegmatites that have been discovered and prospected is on the Owl claim. It is an elongate body which strikes about N. 55° E. and dips 60–75° NW. (Fig. 4). Its greatest exposed width is about six feet. It is at least 12 feet long and has been prospected to a depth of 12 feet in a pit. The mineralogy is similar to that of the other pegmatites,

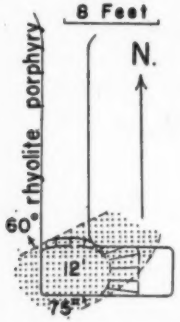


FIG. 4. Sketch of the Owl pegmatite prospect.

but the texture is coarser. One mass of sanidine in the south wall of the pit has dimensions of $2\frac{1}{2} \times 4$ feet. Some of the quartz masses are as large. It was not possible to determine whether the individual masses were one crystal or several. The quartz: sanidine ratio is about 60:40. Smoky, milky, and clear quartz are present in order of abundance as given.

### *Mineralogy.*

*Quartz.*—Quartz is equal to or more abundant than sanidine in the pegmatites, although sanidine is the most abundant mineral of the rhyolite porphyry and its coarser phases. This is undoubtedly a result of concentration of the more acidic constituents during the pegmatite-forming process. It is a noticeable feature that the smoky variety of quartz is successively more abundant in the coarser phases of the intrusive. Thus the rhyolite porphyry contains little or no smoky quartz, whereas in the pegmatite it is the dominant type. Although there are all gradations from clear to milky and smoky quartz, very dark smoky quartz is a prominent feature of the pegmatites. Some of it is jet black. It is generally more highly fractured or shattered

than the milky or colorless quartz. Mohler [3] has shown that the smokiness of quartz can be induced by radioactivity. It is difficult to explain how this alone could have produced smokiness in quartz alongside of clear or milky quartz, unless there was a difference in the clear and milky varieties on the one hand and the smoky on the other. Under the microscope the clear and milky varieties are nearly similar as to content of inclusions, vacuoles, and other dustlike particles. The dark smoky quartz, however, has several times as many of these features, and it would therefore appear that they are an important factor in the cause of the smokiness of the quartz.

No tests have been made of the quartz but it would appear that it may have crystallized as high-quartz because of the closely associated sanidine. Some sanidine euhedrons are imbedded in quartz, and some sanidine has molds of quartz-crystal striations. It would appear, therefore, that the quartz crystallized at the same temperature as the sanidine.

*Sanidine.*—The sanidine occurs as phenocrysts in the rhyolite porphyry and in anhedral grains in the fine-grained and granitoid phases of the intrusive. Within the pegmatites sanidine occurs in anhedral and euhedral forms intergrown with the other minerals, especially quartz. The larger masses of sanidine may be coarse to giant intergrowths of several anhedrons, but single crystals up to $13'' \times 13'' \times 20''$ have been found. Euhedral crystals of sanidine form as pseudo-tetragonal Baveno twins. These invariably have lusterless white coronas which range from about one-sixteenth inch thick in small crystals to as much as one inch thick in large crystals. Under the microscope the corona is a fringe in the sanidine containing numerous opaque white feathery planes arranged diagonally to the crystal faces. These feathery planes appear to be the only cause of the opaque whiteness of the coronas and no other mineral, unless it be very thin films of kaolin, is present in the coronas. No zoning has been observed in the sanidine crystals.

The following optical properties have been determined for the Rabb Canyon sanidine: $n_\alpha = 1.521$; $n_\beta = 1.526$; $n_\gamma = 1.527$. Opt.—; 2V about 13°. Orientation: Ax. pl. $\perp$ 010; $b = Z$. Extinction: $a \wedge X = 7°$.

The mineral yields a strong flame test for potassium.

In hand specimens the sanidine ranges from colorless to smoky with much of it being milky white. All of the sanidine shows some degree of play of colors. However, it is only seen on surfaces nearly parallel to the c-axis and normal to the clinopinacoid. The play of colors is in many delicate shades from milky white to blues and grays. In the colorless and milky varieties the play of colors is either white or limpid blue. The smoky sanidines are of two distinct colors, gray and amber-gray. The gray variety displays a silvery gray play of colors, and the amber-gray variety displays a deep limpid-blue play of colors.

Under the microscope smoky sanidine, like smoky quartz, contains more numerous tiny inclusions than the clear or white varieties. Although thin sections oriented parallel to the pinacoids were examined, little in the way of a preferred arrangement of inclusions was observed. Single inclusions range

[3] Mohler, N. M., A spectrophotometric study of smoky quartz: Am. Mineralogist, vol. 21, p. 258, 1936.

from about 0.0007 to 0.004 millimeter in diameter. These consist of negative crystals and spherical vacuoles. In addition, thread-like tubes and irregular sheeted vacuoles of larger dimensions than the single equidimensional inclusions are present. The tubular and sheeted vacuoles are developed also in dendritic and netted forms. The individual vacuoles are commonly clustered in rainlike hazes or arranged in straight and curved streams. The inclusions do not appear to be a cause of the play of color exhibited by the sanidine. The cause of play of color in sanidine has been explained as due to the presence of the Murchisonite parting which is nearly parallel to the orthopinacoid. The play of colors is probably due to variable interference effects of light reflected from these submicroscopic planes.

*Accessory Minerals.*—The remaining minerals of the pegmatites include oligoclase (cleavelandite variety), biotite, magnetite, ilmenite, and sphene. Small bunches of white cleavelandite are scattered through most of the pegmatites. The plates range up to two inches in diameter. The extinction angles of the plates show a composition of oligoclase ($Ab_{84}$–$An_{16}$).

Biotite is occasionally present in poorly preserved, thin dark-brown sheets about one-sixteenth inch thick and up to two and a half inches in diameter. It is usually associated with smoky quartz and cleavelandite.

In the middle trench on the Rattlesnake claim a ten-inch seam, about one-quarter inch wide, of magnetite and ilmenite was found. The two are irregularly intergrown in about equal amounts. It appears that a small quantity of columbite may be present also because a spectroscopic analysis of some of the material showed in addition to iron and titanium minor amounts of magnesium, manganese, and columbium.

A few small grains of sphene occur locally, and they are usually associated with the cleavelandite.

*Paragenesis.*—An order of crystallization of minerals in the pegmatites is not distinct. Subhedral biotite occurs within masses of smoky quartz and ogligoclase. In thin sections of albite and sanidine the latter appears to replace the former, but the relations are not conclusive of an order between the two. Sanidine is more commonly euhedral against quartz than vice versa. No sharp or pronounced gap in time of crystallization of the minerals is indicated. However, an order of ending of crystallization may be as follows: biotite, oligoclase, sanidine, and quartz. It is to be noted that this is the order of normal igneous rocks and that it deviates from the order in many pegmatites, where cleavelandite generally comes later than potash feldspar.

## *Origin.*

*The Rabb Canyon Deposits.*—The rhyolite porphyry of the Rabb Canyon deposits is the enclosing and parent rock of the pegmatites. Until a general geologic map is completed on the west side of the Black Range the depth at which the pegmatites formed can only be estimated. However, it appears that the pegmatites formed at a relatively shallow depth of possibly one or two thousand feet. It is quite possible that the plug of rhyolite porphyry reached the surface and contributed to the younger volcanic rocks in the region. It is clearly a hypabyssal form.

The porphyritic phases of the plug are finely miarolitic. This condition may be taken not only to indicate some internal contraction with cooling but also to indicate the presence of hyperfusibles, especially water, distilled from the magma. It is almost universally agreed that a concentration of hyperfusibles is necessary somewhere along the line of magmatic changes toward consolidation in order to develop pegmatite.

In the Rabb Canyon pegmatites the field evidence is clear that the pegmatite and pegmatitic minerals formed before crystallization of the rhyolite porphyry. Figure 5 is a sketch of a slab of pegmatite from the Owl claim cut by stringers of rhyotite porphyry. In addition to many examples of this sort

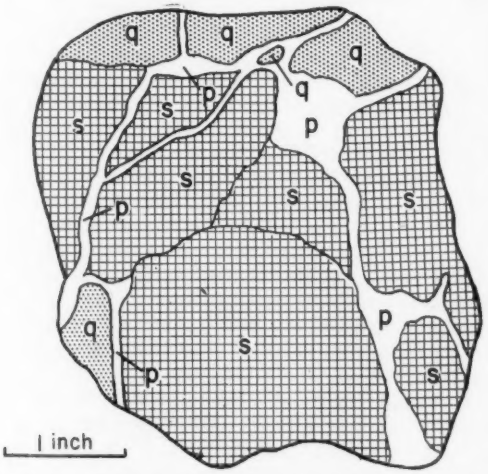


FIG. 5. Sketch of a pegmatite specimen consisting of sanidine (s) and smoky quartz (q) cut by rhyolite porphyry (p).

some single large crystals of sanidine and quartz occur as phenocrysts in the porphyry. Such occurrences find gradations into the large pegmatite masses in the form of small "shots" of pegmatite or what has been termed glomeroporphyritic texture. The pegmatites formed early and before the beginning of crystallization of the porphyry. They may be said to represent the beginning of the crystallization of the plug and may be assigned to the stage of first generation of phenocrysts. A phenocryst may be thought of as a magmatic differentiation or segregation on a minute scale. The formation of the large pegmatite masses was a magmatic differentiation or segregation on a larger scale.

An ascent of granite magma from 15 kilometers to 2 kilometers diminishes the amount of water it can hold in solution from 9.35 to 3.75 percent.[4] If

[4] Goranson, R. W., The solubility of water in granite magmas: Am. Jour. Sci., 5th ser., vol. 22, p. 481, 1931.

the Rabb Canyon intrusive had an excess of about 3.75 percent of water at depth this must have been progressively released during the rise. Furthermore, the liberation of water and other hyperfusibles with ascent of the magma would probably not occur uniformly throughout the rising column due to differential temperatures and turbulent movements in the material. As a result the magma would develop a certain amount of heterogeneity in dissolved water and other hyperfusibles. These might take the form of relatively hyperfusible-rich magma "pockets." It is from these "pockets" that the pegmatite and granitoid phases of the Rabb Canyon rhyolite porphyry appear to have formed. The rhyolite porphyry crystallized from the relatively hyperfusible-lean phase of the magma.

Following Goranson, the water content of the hyperfusible-rich "pockets" would have been only in the order of 3.75 percent. The loss of hyperfusibles by rising magmas probably is the prinicpal reason for the paucity of pegmatites associated with shallow intrusives. It also may be the principal cause of the scarcity and smallness of the pegmatites in the Rabb Canyon intrusive.

It may be noted by reference to Fig. 2 that the pegmatite bodies as known are more nearly grouped in the center of the plug, and that none are known in the periphery or in the country rock. With the situation being what it appears, the hyperfusible-rich "pockets" might have been concentrated in the central area by crystallization of an anhydrous shell. Crosby and Fuller [5] long ago attached much significance to this process following the ideas of Soret and Iddings, but modern petrologists [6] have felt that there are other processes of greater magnitude. It would also appear that concentration of hyperfusibles by crystallization of a shell would be more likely to take place in deep or flat-topped intrusives than in shallow or steep-sided plugs.

*Review of Theories of Origin.*—A modern review of theories of the origin of pegmatite has been given by Landes,[7] and in this work he rather completely cited the important literature dealing with origin. The earlier theories were largely in vogue prior to 1900 and strongly supported by T. Sterry Hunt [8] in this country and others before him in Europe. These theories were largely discarded or assigned to some importance within the realm of metamorphic differentiation.

Around the turn of the century the work of Lehmann, Brögger, Williams, Crosby and Fuller, Spurr, and Hastings [9] redeveloped the earlier expressed theories [10] of igneous origin and emphasized the importance of water and other hyperfusibles in and arising out of the magma. Crosby and Fuller [11] termed

[5] Crosby, W. O. and Fuller, M. L., Origin of pegmatite: Am. Geologist, vol. 19, p. 172, 1897.

[6] Alling, H. L., Interpretive petrology of the igneous rocks, p. 231, 1936.

[7] Landes, K. K., Origin and classification of pegmatites: Am. Mineralogist, vol. 18, pp. 33–56; 95–103, 1933.

[8] Hunt, T. Sterry, Notes on granitic rocks: Am. Jour. Sci., 3rd ser., Pt. III, vol. 103, pp. 115–125, 1872.

[9] Landes, op. cit.: p. 41 and Crosby, W. O., and Fuller, M. L., Origin of pegmatite: Am. Geologist, vol. 19, p. 148, 1897, for earlier references.

[10] Charpentier, J. von, Essai sur la constitution géognostique des Pyrénées, p. 158, Paris, 1823. Elie de Beaumont, Sur les émanations volcaniques et metallifères: Bull. de la Soc. Géol. France, (2), IV, p. 12, 1847.

[11] Op. cit., p. 166.

the pegmatite phase of the magma aqueo-igneous; and others, as Bastin,[12] simply referred to the slightly more hydrous phase as the pegmatite magma. Most succeeding writers have subscribed to the importance of concentrations of water and other hyperfusibles in the formation of pegmatite, and the theory has been indirectly supported by much field evidence.[13] Furthermore, the added effect of later aqueous fluids modifying earlier more nearly magmatic deposits was greatly emphasized. In the late twenties and early thirties Schaller, Hess, Landes, Anderson,[14] and many others developed in considerable detail the paragenesis and mineral sequences in pegmatites, especially the complex ones. Although many of the above workers have described zoning in pegmatites, especially in connection with studies of the genesis of minerals and textures, the real impetus in delineating and evaluating zoning in pegmatites came with the detailed studies made especially by the U. S. Geological Survey during World War II. The detailed work of Johnston, Jahns, Griffitts, Cameron [15] and others has developed the presence of mappable zones within pegmatite bodies. They also related the zones to paragenesis. Genetic theories developing from these studies tend to place less emphasis upon hydrothermal replacements and attach a greater role to successive inward crystallizations out of a pegmatite magma.

*Classification.*—With the development of the modern theories of origin of pegmatites have come several classifications. That the great majority of pegmatites are simple in composition and approximate normal plutonic masses mineralogically, and that some, commonly the larger ones, are complex mineralogically has been long recognized. Schaller and Landes [16] have defined simple and complex pegmatites; the latter, following Palache and Harker,[17] has classified pegmatites compositionally into acidic, intermediate, and basic with simple and complex as subdivisions under each of these. Johnston [18] has classified Brazilian pegmatites into homogeneous (no very large crystals and uniform texture) and heterogeneous (zoned, with very large crystals). Landes [19] gives Piatniksky's genetic classification as follows:

[12] Bastin, E. S., Origin of the pegmatites of Maine: Jour. Geology, vol. 18, p. 308, 1910.

[13] Bastin: op. cit. Kemp, J. F., The pegmatites: Econ. Geol., vol. 19, pp. 697–723, 1924. Hess, F. L., The natural history of the pegmatites: Eng. Min. Jour., vol. 120, pp. 289–298, 1925.

[14] Schaller, W. T., The genesis of lithium pegmatites: Am. Jour. Sci., 5th ser., vol. 10, pp. 269–279, 1925; Mineral replacements in pegmatites: Am. Mineralogist, vol. 12, pp. 59–63, 1927; Pegmatites: Lindgren Volume, Am. Inst. Min. Met. Eng., pp. 144–151, 1933. Hess, F. L., Pegmatites: Econ. Geol., vol. 28, pp. 447–462, 1933; The pegmatites of the Western States: Lindgren Volume, Am. Inst. Min. Met. Eng., pp. 526–536, 1933. Landes, K. K., The paragenesis of pegmatites of central Maine: Am. Mineralogist, vol. 10, pp. 365–411, 1925. Anderson, A. L., Genesis of mica pegmatite deposits, Latah County, Idaho: Econ. Geol., vol. 28, pp. 41–58, 1933.

[15] Johnston, W. D., Jr., Beryl-tantalite pegmatites of northeastern Brazil: Geol. Soc. America Bull., vol. 56, pp. 1015–1070, 1945. Jahns, R. H., Mica deposits of the Petaca district, Rio Arriba County, N. M.: New Mexico Bur. Mines and Min. Res. Bull. 25, 294 pages, 1946. Griffitts, W. R. and others, Mica-bearing pegmatites in the southeastern states: Geol. Soc. America Bull., vol. 56, p. 1162, 1945. Cameron, E. N. and others, Structural and economic characteristics of New England mica deposits: Econ. Geol., vol. 40, pp. 369–393, 1945.

[16] Op. cit.

[17] Harker, A., Natural history of the igneous rocks, p. 298, 1909.

[18] Op. cit., p. 1025.

[19] Op. cit., p. 95.

I. Monophasis pegmatites (a) liquid magma pegmatites, (b) pneumatolytic pegmatites, (c) hydrothermal pegmatites;
II. Polyphasis pegmatites.

Without discounting the importance of composition in the classification it can be said that the genetic classification is the ultimate to be desired. Forthcoming classifications may turn toward the genetic in an effort to improve our understanding of the origin of pegmatites. In addition to factors already used, such as mineralogical complexity, essential composition, character of the fluid, and zoning, other factors that may be considered are: (1) time of formation with regard to the consolidation of the parent magma, (2) parent rock and position of pegmatite with regard to it, and (3) temperature.

*Early Formation.*—The first two factors are related in that the only pegmatites which can give direct evidence as to time of crystallization are those within the parent rock. The composition or clan of the parent rock is of significance. The composition of the pegmatite does not give the entire picture, for not all granite pegmatites have parent rocks of granite. Miller [20] has described silexite, granite pegmatites, and gabbro pegmatites in the North Creek quadrangle of the Adirondack Mountains that developed by segregation from the magma of gabbroic stocks while they were still fluid as well as nearly consolidated. Grout [21] has described granite pegmatites in the border of the Duluth gabbro which he concluded were formed from a pegmatite fluid that segregated from the gabbro magma before it had begun to crystallize. Warren [22] concluded a similar early origin for pegmatites near Quincy, Massachusetts. Many others have suggested an early origin for pegmatites, but there can be no doubt that pegmatite forms at different stages in the consolidation of a plutonite. Miller [23] described early and late pegmatites associated with the Lyon Mountain granite in the Adirondacks, and Grout [24] described early pegmatites in granite crossed by later pegmatites. Recently Heinrich [25] described granite injections into pegmatite.

Most large pegmatites are in the country rock. The impression is gained from reading many papers that the epigenetic nature of these is to some extent a factor in giving undue stress to a late origin for pegmatites. Pegmatite dikes along fractures in the peripheries of granite bodies have been described from many districts; but, on the other hand, too little detailed study has been made of the border relations between granite and pegmatites that are unrelated to fractures. There is little evidence that pegmatites form later than central masses of granite inside early crystallized borders or shells.

[20] Miller, W. J., Pegmatite, silexite, and aplite of northern New York: Jour. Geology, vol. 27, p. 54, 1919.
[21] Grout, F. F., The pegmatites of the Duluth gabbro: Econ. Geol., vol. 13, pp. 185–197, 1918.
[22] Warren, C. H., Note on the occurrence of an interesting pegmatite in the granite of Quincy, Massachusetts: Am. Jour. Sci., 4th ser., vol. 28, pp. 449–452, 1902.
[23] Op. cit., p. 46.
[24] Grout, F. F., Petrography and petrology, p. 221, 1932.
[25] Heinrich, E. W., Composite pegmatites of the Franklin-Sylva mica district, N. C.: Geol. Soc. America Bull., vol. 56, p. 1166, 1945.

The time of formation of the pegmatite and pegmatite fluid needs to be re-examined with special attention given to pegmatites in their parent rock. The field evidence of timing of the large majority of pegmatites is by no means a closed case. Grout,[26] not unwittingly, points to this in reference to the idea of late formations as the *"prevailing notion"* and to the early formation as the *"other notion."*

In a recent preliminary chart of North American pegmatites made by a student under supervision of the senior author, 19 districts were tabulated in which the pegmatites were dominantly in parent igneous rock, and 36 districts in which the pegmatites were dominantly in country rock. About three-fourths of the parent-rock occurrences are in granite, and about 55 percent of the country-rock occurrences are in schist. In many descriptions the enclosing rock of the pegmatites is not recorded. For a complete understanding of the origin of pegmatites of igneous derivation it is essential to study the pegmatite in relation to the parent intrusive. Spectroscopic and accessory-mineral studies may be invaluable in relating pegmatites to intrusive rocks. The most critical genetic studies can be made on those pegmatites within the parent rock. A detailed classification of pegmatites may include a twofold subdivision—parent rock and country rock.

*Temperature.*—As an outgrowth of the methods developed by Wright and Larsen,[27] Bastin [28] concluded that the Maine pegmatites formed near 573° C. The quartz of the graphic granite showed high-quartz ancestry whereas the larger and later masses of quartz did not, having crystallized as low-quartz below 573° C. It has since been felt that most pegmatites crystallize in a range near 573° C. Such a conclusion should perhaps be limited to pegmatites of deep or plutonic origin. Shallow intrusives are thought to have crystallized at temperatures nearer to the temperatures of consolidation for volcanic rocks. Pegmatites within shallow intrusives are rare, but it might have been logically reasoned that they should crystallize at a high temperature.

The contrasting occurrences of microcline, orthoclase, and sanidine are such as to suggest a high temperature origin for sanidine. Merwin [29] deduced from thermal studies of certain alkali feldspars in dry melts that sanidine might form under such conditions at about 900° C. In a hydrous magma under confining pressure the inversion temperature might be considerably different. Although sanidine is generally believed to form at higher temperature than orthoclase, the use of sanidine as a "fixed point" in geologic thermometry is not justified at present.[30] Even though sanidine might form from certain lavas at about 900° C. it does not necessarily form at that temperature under conditions as they were in the Rabb Canyon magma. Nevertheless, in so far as sanidine is a higher temperature and lower pressure form

[26] Op. cit., p. 220.

[27] Wright, F. E., and Larsen, E. S., Quartz as a geologic thermometer: Am. Jour. Sci., 4th ser., vol. 27, pp. 423–447, 1909.

[28] Bastin, E. S., Origin of the pegmatites of Maine: Jour. Geol., vol. 18, pp. 310–319, 1910.

[29] Merwin, H. E., The temperature stability ranges, density, chemical composition, and optical and crystallographic properties of the alkali feldspars: Wash. Acad. Sci. Jour., vol. 1, pp. 59–60, 1911.

[30] Faust, G. T., Written communication, 1947.

among the potash feldspars, the Rabb Canyon pegmatites represent a distinctly new type.

*Geologic Age.*—The geologic age of pegmatites has been broadly considered by Landes.[31] He emphasized the difficulties of detailed tabulation of pegmatites by age, and concluded that they are more numerous in the older rocks because of greater outcrop areas and greater lengths of time represented in the older eras. Since pegmatites are much more commonly deep-seated than shallow-seated in origin, Mesozoic and Cenozoic pegmatite bodies have had less opportunity to be exposed by erosion. Landes [32] listed three pegmatites of Cenozoic age at widely separated areas as follows: (1) Cooke City district, Montana, (2) Carlingford district, Ireland, and (3) northern Italy. There are probably a number of others Dunham [33] has described. Tertiary pegmatites in the Organ Mountains, New Mexico. They appear, however, to be deeper seated in origin than those of Rabb Canyon. The Rabb Canyon pegmatites are probably the shallowest as well as the youngest to have been described.

*Conclusions.*—Shallow high-temperature pegmatites are a new type. Pegmatites may be classified according to depth and temperature similar to hydrothermal vein deposits. There are probably pegmatites equivalent to the depth and temperature zones of the hypothermal, mesothermal, and epithermal mineral deposits. The pegmatites of Rabb Canyon are analogous to the xenothermal, high-temperature, mineral deposits formed at shallow to moderate depth described by Buddington.[34]

Pegmatites of this category are not as numerous as the hydrothermal vein deposits. Simple pegmatites crystallize from hyperfusible-rich magmas. Shallow pegmatites are uncommon with shallow intrusives due to partial loss of the dissolved hyperfusibles. Buddington [35] states, "a mineral association of high temperature . . . moderate to great depth, which has not been found at shallow depths, is that characteristic of complex pegmatites comprising such minerals as the alkali tourmalines, beryl, lepidolite, spodumene, or albite." His statement suggests that he had in mind the possibility of the existence of such a type as the Rabb Canyon pegmatites.

The shallow, high-temperature Rabb Canyon pegmatites are early magmatic in origin. At shallow depths the hyperfusibles necessary to pegmatite formation are not as likely to be retained to the end of normal rock crystallization as at great depth because of the lower pressures. Hence, it may be found to hold true that shallow pegmatites are more commonly early magmatic in contrast to deep pegmatites which are thought to be more commonly late magmatic.

UNIV. OF NEW MEXICO,
ALBUQUERQUE, N. MEX.,
*Oct. 20, 1947.*

[31] Landes, K. K., Age and distribution of pegmatites: Am. Mineralogist, vol. 20, p. 81, 1935.
[32] Op. cit., p. 85.
[33] Op. cit., p. 112.
[34] Buddington, A. F., High temperature mineral associations at shallow to moderate depths: ECON. GEOL., vol. 30, pp. 205–222, 1935.
[35] Op. cit., p. 209.

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# ORE DEPOSITS AND GEOLOGIC AGE.

STANKO MIHOLIĆ.

ABSTRACT.

The content of heavy metals in mineral waters differs according to the age of faults with which the occurrence of the mineral water is connected. As available data are scarce, this regularity has been investigated for two regions in detail and found in agreement with the proposed hypothesis. The occurrence of ore deposits shows a similar, although not so clear, regularity. The reasons for this regularity are to be looked for, first in the more advanced erosion of the older strata thus exposing deeper parts of the faults, and second in the decrease of the geothermal gradient with time owing to the decrease of radioactive matter in the earth's crust.

It is nowadays generally admitted that the conventional chemical and physico-chemical analyses cannot account entirely for the pharmacological effect of a mineral water. A number of explanations have been suggested in the last thirty years to account for this effect (radioactivity, colloids, iron and manganese in a specific ionic form). The author has tried to approach the question from another angle. It is well known that heavy metals (other than iron and manganese) even in minute quantities exert a marked pharmacological effect and it was decided to look for them in mineral waters too. For this purpose the author undertook an investigation to determine the content in heavy metals of various mineral waters in Yugoslavia and abroad, principally in order to detect the possible reason why some mineral waters, while greatly similar in their macrochemical composition, radioactivity and physical behavior, show a marked difference in their pharmacological and therapeutic action. For some of those waters it has been established that their content in heavy metals is wholly different.

During this work the author noticed that a certain parallelism exists between the geologic age of the joints and faults and the content in heavy metals in mineral waters connected with them. It has been shown [1] that waters containing uranium, or the products of its radioactive disintegration in greater concentration, are connected with Late Archaic Tectonics (Algoman Orogeny), those with predominating nickel with Proterozoic Tectonics (Keweenawan Orogeny), those with predominating copper with Caledonian movements, those with predominating tin with Hercynian movements. To the Older Alpine movement (Cretaceous and Early Tertiary) correspond waters containing zinc as the main heavy metal, to the Younger Alpine movement (Miocene) those containing lead, and mercury is connected with

[1] Miholić, S., Das Vorkommen von Schwermetallen in Mineralwassern: Chemie der Erde 8, pp. 440–445, 1933. Miholić, S., The occurrence of heavy metals in mineral waters: XV^e Congrès international d'Hydrologie, de Climatologie et de Géologie Médicales, pp. 589–600, Belgrade, 1936.

tectonic movements that are still going on. Besides the predominating heavy metal, the mineral waters may contain smaller amounts of other heavy metals, but in a given mineral water always one metal predominates.

The number of mineral waters however, where determinations of their content in heavy metals were made, is still rather small, their sources widely scattered, and also the tectonic conditions of their surroundings often still controversial. The above mentioned parallelism could, therefore, be considered as merely accidental. It seems advisable to discuss smaller areas where a greater number of analyses of waters are available and whose geology has been studied in detail. Two such areas were chosen: One lies in the NW corner of Yugoslavia and adjacent parts of Austria where Pohorje (Bacher Mountain), the Koralpe and the Stubalpe are the main geologic features; the other is the great rift valley (Mjösen Lake-Mediterranean zone) that can be followed, although partly obliterated by subsequent tectonic movements, or filled in by later deposits, from southern Norway through the Upper Rhine Valley, Rhone Valley to the Mediterranean.

Between the easternmost spur of the Alps and the adjoining Dinarides there are remnants of a much older formation (Stubalpe-, Koralpe- and Bacher-Mountains) which, according to A. Winkler,[2] played an important role in the ultimate shaping of this part of the Alpine System. The formation and its surroundings show a number of faults, the most important of them being the Lavant Valley fault,[3] which is also morphologically the most marked one. It starts in Carinthia at Möderbrugg northwest of Judenburg, stretches in sections for 150 kilometers in a SSW direction to the south foot of the Boč (Wotsch) Mountain, each section being shifted towards the west, turns east to Rogaška Slatina and, according to the Austrian geologists (R. Hoernes, A. Winkler and A. Kieslinger), disappears in a northeasterly direction under the younger sediments of the Pannonian Plain. It would seem however more appropriate to connect it with the fault that follows due east the northern foot of the Ivančica and Kalnik Mountains which has been established by Croatian geologists (M. Kišpatić, D. Gorjanović[4] and J. Poljak[5]). According to F. Heritsch,[6] A. Kieslinger and A. Winkler[7] the fault was formed in the Upper Cretaceous. For its eastern continuation on the foot of Mt. Kalnik, J. Poljak claims an Upper Jurassic or Lower Cretaceous age. The fault was partly reactivated during Miocene, locally even later.

The second fault stretches from Medijske Toplice in Slovenia ENE of Ljubljana and follows the southern foot of the Ivančica and Kalnik Mountains.[8]

[2] Winkler, A., Die Bedeutung des Alpen-Dinariden Problems für den Alpenbau: Jahrbuch geol. Bundes-Anstalt 78, pp. 221–240, 1928.

[3] Kieslinger, A., Die Lavanttaler Störungszone: Ibid. 78, pp. 499–527, 1928.

[4] Gorjanović, D., Explanation to the geological map Rogatac-Kozje, p. 21, Zagreb, 1904.

[5] Poljak, J., Prilog poznavanju geologije Kalničke gore: Vjestnik hrv. drž. geol. zavoda 1, pp. 53–92, 1942.

[6] Heritsch, F., Beiträge zur geologischen Kenntnis der Steiermark. V. Die Tektonik der Wotschgruppe bei Pöltschach in Untersteiermark: Mitteilungen d. naturwiss. Vereines für Steiermark 50, pp. 84–94, 1914.

[7] Winkler, A., Über tektonische Probleme in den Savefalten: Jahrbuch geol. Bundes-Anstalt 80, pp. 351–378, 1930.

[8] Miholić, S., Kemijska analiza termalnih vrela u Hrvatskom Zagorju: Rad jugosl. akad. 267, pp. 195–215, 1940.

The third fault starts south of the river Save, and follows first a NE and then a ENE direction and finally converges with the second fault. The fourth fault [9] follows first the SE foot of the Gorjanci Mountain, crosses the Save and skirts the NW foot of the Medvednica Mountain. Older authors (D. Gorjanović) believed that all those faults have been formed during Miocene, while later authors (J. Paljak) consider that they have been formed during the Upper Jurassic or Lower Cretaceous. Most of them have been reactivated in Miocene and in some places were movements as late as Pleistocene.

TABLE I.

CONTENT IN HEAVY METALS OF MINERAL WATERS BELONGING TO THE POHORJE ZONE.

| Locality | Heavy metals in parts per million | | | | | Analyst |
|---|---|---|---|---|---|---|
| | Ni | Cu | Sn | Zn | Pb | |
| Sicheldorf, Austria | | 0.0070 | 0.0020 | 0.0839 | 0.0174 | S. Miholić |
| Boračova, Yugoslavia | | | | | | |
| Royal Well | | | | 0.0593 | 0.0102 | S. Miholić |
| Gizela's Well | | | | 0.0324 | 0.0021 | S. Miholić |
| Slatina Radenci Yugoslavia | | | | | | |
| Medicinal Well | | | | 0.0248 | 0.0088 | S. Miholić |
| Vilma's Well | | | 0.0046 | 0.0403 | 0.0127 | S. Miholić |
| Bathhouse Well | | | | 0.0543 | 0.0158 | S. Miholić |
| Očeslavci, Yugoslavia | | | | 0.0451 | 0.0110 | S. Miholić |
| Gabernik, Yugoslavia | | | | | | |
| Maria's Well | | 0.0111 | 0.0140 | 0.0514 | 0.0183 | S. Miholić |
| Kostrivnica, Yugoslavia | | | | | | |
| Royal Well | | 0.0232 | 0.0082 | 0.0543 | 0.0071 | S. Miholić |
| Rogaška Slatina Yugoslavia | | | | | | |
| Tempel Well | | | | 0.0441 | | V. Majer |
| Dobrna, Yugoslavia | | 0.0160 | | 0.0340 | | M. Samec and L. Guzelj |
| Krapinske Toplice Yugoslavia | | | | | | |
| Jacob's Source | | | 0.0008 | 0.0240 | 0.0141 | S. Miholić |
| Stubičke Toplice Yugoslavia | | | | | | |
| Main Source | trace | 0.0044 | 0.0004 | 0.0679 | 0.0025 | S. Miholić |

There is no doubt that those faults are closely connected with the formation of the Dinarides further to the south and southeast which took place at the limit between the Lower and the Upper Cretaceous.[10]

The magmatic intrusive connected with those faults that now forms the greater part of the areal of the Bacher Mountain, has only recently been determined as tonalite. Its age is now generally considered as probably Cretaceous (F. Heritsch,[11] L. Dolar-Mantuani [12]).

[9] Miholić, S., Kemijska analiza termalnog vrela u Stubičkim Toplicama: Ibid. 278, pp. 195–211, 1945.

[10] Pilger, A., Paläogeographie und Tektonik Jugoslawiens: Neues Jahrbuch für Mineralogie, Beil.-Bd. 85, Abt. B., pp. 383–462, 1941.

[11] Heritsch, F., Beiträge zur geologischen Kenntnis der Steiermark. IV. Studien im Gebiete des westlichen Bachers: Mitteilungen d. naturwiss. Vereines für Steiermark 50, pp. 52–79, 1914.

[12] Dolar-Mantuani, L., Razmerje med tonaliti in apliti Pohorskoga masiva: Annales géologiques de la péninsule balkanique 12, pp. 1–164, 1935.

If we now compare the content in heavy metals in some of the numerous mineral springs connected with the faults (Table I), we find without exception that zinc is the predominant metal, in complete agreement with the hypothesis as set forth in the introduction.

The zone Mjösen Lake-Mediterranean is composed of several elements, each of which shows a shift towards the west as one proceeds from north to south. There is also a slight variation in character. In Scandinavia it is a plain rift valley. The same is the case farther south in the Upper Rhine Valley and, to a lesser extent, in the Saone-Rhone Valley. In Hessen, north of the Upper Rhine Valley, the zone shows, besides its characteristic faults, a great number of faults that are more or less perpendicular to the direction of the former. Contrary to the conditions in the Upper Rhine Valley, where the vertical displacements amount to several thousand meters, the displacements here are small. Farther north, in the North German Plain and in

TABLE II.

CONTENT IN HEAVY METALS OF MINERAL WATERS BELONGING TO THE MJÖSEN LAKE-MEDITERRANEAN ZONE.

| Locality | Heavy metals in parts per million | | | | | | Analyst |
|---|---|---|---|---|---|---|---|
| | Ni | Co | Cu | Sn | Zn | Pb | |
| Strömstad, Sweden | | 0.13 | | | | | N. P. Hamberg |
| Ronneby, Sweden | | | | | | | |
| Old source | 0.038 | 0.015 | | | 0.766 | | C. Th. Mörner |
| Ekholtz källan | 2.656 | 2.649 | | | | | N. P. Hamberg |
| Abelins källan | | | | | 3.953 | | C. Th. Mörner |
| Berzelius källan | | | | | 0.211 | | C. Th. Mörner |
| Melle, Germany | | | | | | | |
| Alte Quelle | | | 3.2 | | | | |
| Pyrmont, Germany | | | | | | | |
| Brodelbrunnen | | trace | | | | | |
| Salztrinkquelle | trace | | trace | | 0.115 | | E. Hintz and L. Grünhut |
| Wolfgangsquelle | | | 0.49 | | | | |
| Berlin, Germany | | | | | | | |
| Bonifazius-Quelle | | | trace | | trace | | R. and H. Fresenius |
| Driburg, Germany | | | | | | | |
| Caspar-Heinrich-Quelle | | | | | trace | | R. and H. Fresenius |
| Alexisbad, Germany | | | | | | | |
| Selkebrunnen | | | 4.48 | | 1.73 | | |
| Ernaquelle | | | 2.689 | | | | |
| Volkmarsen, Germany | | | | | | | |
| Sauerbrunnen | | | 0.05 | | 0.01 | | |
| Kreuzburg, Germany | | | | | | | |
| Karolinen-Quelle | | | | | trace | | E. Hintz |
| Ronneburg, Germany | | | | | | | |
| Eulenhöfer Quelle | 0.024 | | | | 0.030 | | R. Fresenius and E. Hintz |
| Hersfeld, Germany | | | | | | | |
| Lullusbrunnen | | | | | 4.304 | | E. Hintz and L. Grünhut |
| Salzschlirf, Germany | | | | | | | |
| Bonifatiusquelle | | | trace | | | | |
| Essen, Germany | | | | | | | |
| Burgwallbronn | | | | | 0.05 | | |
| Bad Nauheim, Germany | | | | | | | |
| Kurbrunnen | | | | | 2.50 | | |
| Karlsbrunnen | | | | | 2.60 | | |
| Sprudel VII | | | | | 2.20 | | |
| Sprudel XII | | | | | 3.90 | | |
| Sprudel XIV | | | | | 4.10 | | |
| Aachen, Germany | | | | | | | |
| Kaiserquelle | | | 0.04 | | 0.14 | | |
| Schwertbadquelle | | | 0.067 | | | | |
| Rosenbadquelle | | | 0.04 | | 0.15 | | |
| Neuenahr, Germany | | | | | | | |
| Grosser Sprudel | | | trace | | trace | trace | E. Hintz and L. Grünhut |
| Willibrordusquelle | | | 0.03 | | | | |
| Sinzig, Germany | | | | | | | |
| Fontinalis Sprudel | | | | | 0.147 | | E. Hintz and L. Grünhut |

TABLE II.—*Continued.*

| Locality | Heavy metals in parts per million | | | | | | Analyst |
|---|---|---|---|---|---|---|---|
| | Ni | Co | Cu | Sn | Zn | Pb | |
| Arienheller Bad, Germany | | | | | | | |
| Sprudel | | | trace | | trace | | E. Hintz |
| Niederbreisig, Germany | | | | | | | |
| Gertrudisquelle | | | | | 0.06 | | |
| Brückenau, Germany | | | 0.0895 | 0.0044 | | | Keller |
| Bad Orb, Germany | | | | | | | |
| Martinusquelle | | | trace | | 0.317 | | E. Hintz and L. Grünhut |
| Rhens, Germany | | | | | | | |
| Sprudel | | | | | trace | | E. Hintz and L. Grünhut |
| Birresborn, Germany | | | | | | | |
| Heilquelle | | | | | 0.13 | | |
| Lindenquelle | | | trace | | 0.129 | | E. Hintz and L. Grünhut |
| Saalfeld, Germany | | | | | | | |
| Heilquelle | | | 23.1 | | | | |
| Linda, Germany | | | | | | | |
| Moorstichquelle | 5.32 | | 5.96 | | 55.80 | | |
| Höllensprudel b. Steben, | | | | | | | |
| Germany | 0.029 | 0.0086 | trace | | 0.043 | | E. Hintz |
| Wiesbaden, Germany | | | | | | | |
| Kochbrunnen | | | trace | | | | |
| Schützenhofquelle | | | trace | | | | H. Fresenius |
| Kleine Schützenholquelle | | | trace | | | | R. Fresenius |
| Schlangenbad, Germany | | | | | | | |
| Römerquelle | | | 0.013 | | | | |
| Kreuznach, Germany | | | | | | | |
| Elizabethquelle | | | | | 3.673 | | R. and H. Fresenius |
| Victoriaquelle | | | | | 0.143 | | R. and H. Fresenius |
| Mondorf, Luxemburg | | | trace | | | | van Kerckhoff |
| Teinach, Germany | | | trace | trace | | trace | Fehling |
| Rippoldsau, Germany | | | | | | | |
| Josephsquelle | | | 0.0798 | 0.0220 | | 0.0232 | H. Will |
| Leopoldsquelle | | | 0.1015 | 0.0335 | | 0.0344 | H. Will |
| Wenzelsquelle | | | 0.0559 | 0.0150 | | 0.0145 | H. Will |
| Niederbronn, France | | | trace | | | trace | O. Haenle |
| Rappoltsweiler, France | | | | | | | |
| Source Carola | | | | | 0.502 | | R. Fresenius and E. Hintz |
| Contrexeville, France | | | 0.007 | | | | M. J. Golse |
| Bourbon-l'Archambault, | | | | | | | |
| France | | | trace | | | | |
| Vichy, France | | | | | | | |
| Grand Grille | | | | trace | trace | trace | G. Urbain and J. Bardet |
| Saint-Nectaire, France | | | | trace | | | M. Garrigou |
| Source du Rocher, | | | | | | | |
| Puy-de-Dôme, France | trace | trace | trace | | 0.0153 | trace | M. Garrigou |
| Urriage, France | | | | | trace | trace | M. G. Massol |
| Lamalou, Hérault, France | trace | trace | trace | | | trace | |

Denmark, the zone has been covered by Tertiary and Quaternary sediments and only geophysical investigations (*e.g.* the determination of gravity) have shown its existence at depth.[13]

The northern section of the zone represents its oldest part and the faulting has proceeded by stages southward. In the Mjösen Lake district (Norway) the faulting began in the Permian, but the main movements occurred in the Early Tertiary and caused displacements amounting to thousands of meters. Farther south the zone disappears under the younger sediments of the North German Plain and emerges only in Hessen (Leine Rift Valley). According to the investigations of H. J. Martini [14] in the region around Cassel, the faults were formed during Late Jurassic or Early Cretaceous and some of them were locally revived during the Tertiary. The same results were obtained by

[13] Kossmat, F., Die mediterranen Kettengebirge in ihrer Beziehung zum Gleichgewichtszustande der Erdrinde, 2nd ed., pp. 52–57, Leipzig, 1926.

[14] Martini, H. J., Grossschollen und Gräben zwischen Habichtswald und Rheinischen Schiefergebierge: Geotektonische Forschungen 1, pp. 69–123, 1937.

G. Seidel [15] and W. Carlé [16] for the regions adjoining to the north and by E. Lemke [17] and F. K. Mixius [18] for parts of the zone lying towards the south. The age of the formation of the Upper Rhine Valley has been fixed as later than Jurassic and earlier than Tertiary.[19] Later investigators (W. Wagner and H. Stille [20]) consider the main faulting decidedly older than Oligocene, but vertical movements in the valley occurred as late as Pleistocene. The first faults bordering the Rhone Valley on the west appeared at the end of the Paleozoic and in the Triassic were again active in the Middle Jurassic, but the main faulting occurred during the Oligocene, although movements along them continued into the Pliocene. The eastern border of the valley is formed by the folds of the Préalps.

Thus the main faulting in the Mjösen Lake-Mediterranean zone took place in the Cretaceous and Early Tertiary.

Table II, which gives all available analyses of mineral waters of the region, shows that a great majority of the mineral waters in the zone and its nearest surroundings contain zinc as the main metal in accordance with the hypothesis. Even most of those mineral waters in Germany that contain copper instead, can be accounted for by the hypothesis, as the majority of them occur in a belt stretching W–E between Brabant and Lower Silesia, where there is ample evidence of Caledonian movements.

As hydrothermal activity is so closely connected with the formation of ore deposits, the question arises: can a similar connection be established between the ore deposits of magmatic or hydrothermal origin and the age of the joints and faults in which they have been formed? This is in fact the case, although the regularities are not so clear as with the mineral waters. The reasons are obvious. While the mineral water that now flows through the old faults represents so to say an average mean value of the metallization of those faults through which it is flowing, the ore deposits represent individual formations, where often leaching and redeposition have changed to a marked degree the original conditions.

In order to investigate this point, a statistical method has been employed. Percentages of world production given for different countries in the World Atlas of Commercial Geology, Part I [21] for 1913 and by David Williams [22] for 1938, have been compared with the geologic age of the deposits in question, as recorded in the literature. For obvious reasons no data are available for the world production of uranium. Still the age of the most important deposits

[15] Seidel, G., Die Dislokationszonen zwischen Bonenburg und Volkmarsen: Ibid. 3, pp. 1–32, 1938.

[16] Carlé, W., Die saxonische Tektonik westlich und nordwestlich des Harzes (Gittelder Graben und Lutterer Sattel): Ibid. 3, pp. 33–72, 1938.

[17] Lemke, E., Der tektonische Bau des Gebiets zwischen Vogelsberg und Rhön: Ibid. 1, pp. 28–68, 1937.

[18] Mixius, F. K., Das hessische Grabengebiet im Süden der Sollingscholle: Ibid. 5, pp. 60–123, 1940.

[19] Suess, E., La face de la terre, Vol. I, p. 262, Paris, 1921.

[20] Stille, H., Rheinische Gebirgsbildung im Kristiania-gebiete und in Westdeutschland: Abh. Pr. Geol. Landesanst., N.F., 95, p. 110, 1925.

[21] World Atlas of Commercial Geology, Part I, U. S. Geol. Survey, Washington, 1921.

[22] Williams, David, Mineral resources of the world: The Advancement of Science 3, p. 206, 1945.

at the Great Bear Lake in Canada and at Katanga in the Belgian Congo has been determined. For the former W. D. Urry [23] gives an age of 900 million years, for the latter C. Stansfield Hitchen and René van Aubel [24] the age of 683 million years. The former value would correspond to the Algoman Orogeny. For the other heavy metals the values are given in Table III which represent the average for the recorded values for 1913 and 1938.

TABLE III.

PERCENTAGE DISTRIBUTION OF THE WORLD PRODUCTION OF SOME HEAVY METALS ACCORDING TO THE AGE OF THEIR ORE DEPOSITS.

| Metal | Age of deposit | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Proterozoic | Paleozoic | | Mesozoic | Tertiary | | Quaternary | Undetermined |
| | | Older | Younger | | Older | Younger | | |
| Ni | 86 | — | — | — | 11 | — | — | 3 |
| Cu | 18.2 | 20.5 | 1.6 | 20.3 | 12.7 | — | — | 26.7 |
| Sn | — | — | 62.5 | — | 17.8 | — | — | 19.7 |
| Zn | — | — | 13.1 | 53.7 | 10.4 | — | — | 32.8 |
| Pb | — | — | 17.1 | 25.6 | 16.0 | 3.0 | — | 38.3 |
| Hg | — | — | — | — | — | 86.3 | 4.2 | 13.7 |

A comparison of the values given in Table III shows good agreement between the percentage distribution of the world production and the age of formation of the ore deposits for nickel and mercury, a fair one for tin and zinc, and the values for copper and lead are not conclusive.

The theoretical explanation of the recorded regularities can be sought for along two lines. The character of a mineral deposit depends primarily on the temperature of its formation and this in turn largely on the depth at which the deposit is formed. Now older orogenic elements are eroded to deeper levels and expose metallic veins formed at greater depths and higher temperatures (uranium, nickel, copper, tin), while the younger orogenic elements are generally eroded only superficially and expose veins formed at low temperatures and at higher levels (zinc, lead, mercury).

Even more important is the gradual decrease of the geothermal gradient during geologic time. The mathematical theory of the cooling of the earth and the decrease of the geothermal gradient has been given by Lord Kelvin.[25] The discovery of the radioactivity of the earth's crust has shown however that this theory is based on erroneous premises. J. Joly [26] has worked out an ingenious hypothesis to account for the periodicity of the orogenic movements taking the geothermal gradient as constant: The heat developed by the dis-

[23] Urry, W. D., Determination of the radium content in rocks: Jour. of Chem. Physics 4, pp. 40–48, 1936.

[24] Hitchen, C. Stansfield, and van Aubel, René, Composition and age of crystalline uraninite from Katanga: Compte rendu. 199, pp. 1135–1175, 1934.

[25] Kelvin, Lord, and Tait, P. G., Treatise on Natural Philosophy, Part II, p. 478, Cambridge, 1903.

[26] Joly, J., The movements of the earth's surface crusts: Phil. Mag. 45, pp. 1167–1188, 1923 and 46, pp. 170–177, 1923.

integration of radioactive elements accumulates in the lower parts of the earth's crust until the melting heat of the basaltic rocks comprising those parts is reached. An intensive orogenic and volcanic activity ensues until the heat is spent and the equilibrium established again. The process of heating recommences then anew. The length of those cycles has been established from geologic evidence as about 190 million years. From North American evidence some geologists conclude that the intervals are becoming shorter in the course of earth's history. Theoretically, however, one should expect that the periods of orogenic movements should grow longer with time and that their intensity should decrease. In fact newer measurements of geologic time have established for the Mesozoic and the Tertiary a much longer duration than was supposed before and the Alpine Orogenic Movements were confined to a much narrower zone than its predecessors. Through radioactive disintegration the amount of radioactive matter in the earth's crust is steadily decreasing. The content in uranium has decreased during geologic time (*i.e.* in the last two billion years) about 23 percent, thorium 7.5 percent, actinium more than 99 percent, the radioactive isotope of potassium 64 percent. Moreover there is ample reason to believe that in addition to those radioactive series, others have existed on the earth in the past. As their disintegration went on at a much quicker pace, they no longer exist, accounting for a number of "extinct" chemical elements that have only recently been prepared artificially. It is obvious that with decreasing radioactivity the geothermal gradient must have decreased too. This fact would therefore also contribute to the explanation of the discussed parallelism between ore deposits and geologic age.

31 Gjorgjićeva,
Zagreb, Croatia,
*October 18, 1947.*

# MINERAL DEPOSITS OF MAGMATIC ORIGIN.

DJALMA GUIMARÃES.

## Introduction.

In earlier papers the author drew attention to the deadlock recorded in certain petrogenetic problems arising from the moment of inertia acquired by old concepts that, although actually obsolete, project themselves longer than should be expected, in view of their absence of physico-chemical grounds and incompatibility with the principles of modern crystallo-chemistry.

Several decades have elapsed since the crumbling of concepts on the molecular constitution of silicates and of "solid solution" brought about by the advancement of physical-chemistry mostly in the field of atomic theory applied to crystal structure revealed by X-Rays. Nevertheless, mineralogenetic problems are studied today as though nothing had ever happened. It must, therefore, be admitted that the admirable available field unlocked by enlightenment in crystal structure and crystallo-chemistry—utterly propitious to a thorough renewal of ideas—has only been remotely tapped.

To promote the best possible understanding of the thesis being presented here and which the author wishes to defend, it seems expedient and pertinent to discuss and elucidate its fundamentals. V. M. Goldschmidt states in his "Kristallchemie" (Göttingen, 1934):

> Die Silikate sind Ionengitter, deren Anionen aus Silicium-Sauerstoffkomplexen oder aus Silicium-Aluminium-Sauerstoffcomplexen bestehen. Als Kationen kommen alle ausgesprochen elektro-positive Elemente in Betracht. Beim Ersatz eines Kations durch ein anderes kommen die gleichen Isomorphie-beziehungen zur Auswirkung, die wir aus dem Verhalten der einfachen Ionensalze kennen. So kann Magnesium durch Nickel oder zweiwertiges Eisen ersetzt werden, Calcium durch Strontium, Yttrium durch die Lanthaniden der Reihe Samarium-Cassiopeium. Auch bei den Silikaten kennen wir Beispiele von Isomorphiebeziehungen mit gegenseitigen Ersatz von Atomen verschiedener Wertigkeit. Das berühmteste Beispiel ist die Isomorphie zwischen Natronfeldspat, $NaAlSi_2O_8$, und Kalkfeldspat, $CaAl_2Si_2O_8$ . . . (7).[1]

In view of the foregoing citation it can be seen why the usual expression "solid solution series" should be dropped, since it finds neither echo nor meaning in the modern physical-chemistry of silicates, and conveys a deceptive notion which makes it unwanted. In another publication (11), the author has demonstrated the inconsistency of the theory of solid solution, on which innumerable petrogenetic investigations are based. He has asserted that this very theory has been responsible for the restraint in mineralogenesis evolution for a long time. Worse, however, is the fact that such theory has misled the researchers, bringing about false interpretations of countless mineral

[1] Figures in parentheses refer to Bibliography at end of paper.

structures (intergrowth), which, were they studied under the light of actual knowledge of crystalline lattice, the solution of several questions would undoubtedly have been found.

For example, take one of the numerous consequences: the unwillingness to accept the phenomenon of diffusion in mineralogenetic processes as really functioning on a large scale. Objection confronting the evidence of such phenomenon is to be ascribed to the persistence of that old and questionable molecular conception.

Goldschmidt recalls that P. V. Groth, the widely known German crystallographer, had long before emphasized the inconsistency of the molecular theory of crystal constitution, summarizing his beliefs as follows:

P. V. Groth hat bereits sehr frühzeitig, ausgehend von gewissen Betrachtungen der geometrischen Gittertheorie, die Vermutung geäussert, dass in Kristallen nicht Moleküle als die eigentlichen Bausteine zu betrachten seien, sondern dass Kristalle aus Gittern der einzelnen Atomarten aufgebaut sein Könnten, und dass diese Atomgitter in regelmässiger weise ineinandergestellt seien. Er hat somit das Aufbauprinzip der sog. Koordinationsgitter vieler anorganischer Verbindungen in gewissen Sinne vorausgesehen (7).

Considerations of the foregoing kind, we insist, must be made because it seems certain that the distinction between the two lines of thought is much deeper than would appear at first sight, and its significance, farther ranging than a mere change in terminology.

Ionic constitution of crystals explains satisfactorily the reactions between solid and liquid phases subject to variations of pressure and temperature, if diffusion is one of the main factors. This covers transformation of minerals due to the ionic migration from a solid phase to a liquid one (residual magma), and from the latter, into a solid one. An adequate example is afforded when transformation of diopside into hypersthene or enstatite already studied (6, 11), takes place when there are favorable conditions in ortho-magmatic phases.

Considerations of permeability or tolerance of crystalline network to ionic penetration as a condition for the substitution, are additional features that ensue from the disclosure, made by atomic theory, of an immense field of investigation giving probabilities of solution to problems which before could hardly have been broached.

If solutions of magmatic origin be regarded as true electrolytes that conduct ions in dissimilar status of concentration, metasomatic processes are given a cogent approach. Furthermore, difference of concentration between liquid and solid phases—being the latter represented by the percolated rock—determines the process of substitution. Of course, additional physico-chemical factors intervene, such as affinity, ionic network's receptivity of pre-existing minerals, and a larger or smaller accumulation of energy produced by the status of ionic vibration. In a remarkable study, Boris Brajnikov (12) shows the striking percentage of void in silicate crystals, however closed is their structure. Taking into account the number of atoms per cubic centimeter, he calculated the oxygen concentration of nearly a hundred minerals of the most common eruptive, metamorphic and sedimentary rocks. He estimated the volume of the boundary sphere of $O^{--}$ ions, so that the remaining space

must either be void or occupied by ions of other elements. Whereas Si and Al ions are enveloped within closed groups of tetrahedral or octahedral oxygen-ions, cations are distributed within the rest space (12). Extreme values found for void were: 33.58% (disthen) and 68.27% (sodalite).

For the best possible comprehension, the same author made available the data from which Table I was compiled, and by which one can check the high percentage of voids in albite, anorthite and diopside, given due consideration to the cations.

TABLE I.

ALBITE D = 2.62.

| | O | Si | Al | Na | Total Atomic Volume | % of Void |
|---|---|---|---|---|---|---|
| Volume of atoms* | $0.467 \times 10^{24}$ | $0.0052 \times 10^{24}$ | $0.0048 \times 10^{24}$ | $0.024 \times 10^{24}$ | $0.501 \times 10^{24}$ | 49.90 |

ANORTHITE D = 2.75.

| | O | Si | Al | Na | Total Atomic Volume | % of Void |
|---|---|---|---|---|---|---|
| Volume of atoms* | $0.462 \times 10^{24}$ | $0.0035 \times 10^{24}$ | $0.0094 \times 10^{24}$ | $0.0259 \times 10^{24}$ | $0.5008 \times 10^{24}$ | 49.92 |

DIOPSIDE D = 3.25.

| | O | Si | Mg | Ca | Total Atomic Volume | % of Void |
|---|---|---|---|---|---|---|
| Volume of atoms* | $0.584 \times 10^{24}$ | $0.0059 \times 10^{24}$ | $0.0179 \times 10^{24}$ | $0.0436 \times 10^{24}$ | $0.6514 \times 10^{24}$ | 34.86 |

* Figures refer to 1 cubic centimeter of substance.

Data from Boris Brajnikov.

As regards diopside, whose 34.86% of void is slightly above the minimum verified (disthen), we must bear in mind that the possibility of its transformation into hypersthene by ortho-magmatic diffusion of Ca, Mg and Fe (11), has been already proved.

Upon investigating his own data, Brajnikov (12) draws the following conclusion:

> This "volume of voids" is astonishingly large for numerous minerals and leads us to believe that they must be relatively "permeable" to many ions; in other words, that diffusion followed by ex-solutions and transformations must be quite easily produced in the minerals of low oxygen concentration: feldspars, for instance. The same occurs in the contact of two phases, a fact that should explain innumerable contact-reactions remarked in thin section of rocks. Such possibility of diffusion would be normally increased by deformations in the crystalline network, in consequence of stress or of rise in temperature (12, p. 336).

As to the infiltration of magmatic emanations through sedimentary rocks, the following quotation from Shand (5, p. 224) proves the point:

> It has been demonstrated experimentally by P. W. Bridgman that a pressure equal to the weight of 17 miles of rocks is not able to close all the pores in rocks. Some proportion of connate water must therefore be retained even in the deepest sediments. It may be heated and set into circulation by intrusive magma, and to a certain extent it may be activated by the fugitive constituents of such a magma. . . .

Permeability of sedimentary rocks performs an important task in the transference of dispersed elements scattered in sediments; hence, my opinion is in full agreement with Shand's regarding elements that form mineral veins. As to alkaline substances, though, I dissent with Shand, who believes that sediments can provide a proportion of them sufficient for wholesale granitization. Here one is compelled to recourse, as in previous works, to the repetition of superposition of effects. In any event, even in a single cycle of magmatic evolution quantities of material transferred from magma to surrounding formation can be immense, as shown by Shand:

> Studies of contact metamorphism often demonstrate a wholesale transference of silica, alkalies, and iron, as well as chlorine and sulphur from the magma to the country rock . . . (p. 42, op. cit.).

After giving some examples, Shand quotes data from J. Gilluly confirming such geochemical feature of magmatic activity. In studying the feldespathization of quartzites by magmatic emanations, Shand mentions W. B. Wright and D. L. Reynolds (p. 46), who prove the real diffusion of elements such as Al, K, and Na, from magma to quartzite.

Reactivation by a new influx of thermal energy determines the migration of elements thus ionized in combination with "volatile elements" of magmatic origin, incorporated into the magma by assimilation of "sial."

The pressure of infiltrating gases, together with the difference of temperature, are sufficient to create haloes of different ionic concentration, and therefore difference of electro-osmotic potential, so that migrating processes are produced through surrounding geologic formation, along capillary fissures or through crystalline network of pre-existing minerals that function as osmotic membranes. In less deep geologic levels, that is, in zones of ruptural deformation, solutions are canalized along fractures, cleavages and joints. Niggli figures that this geo-chemical process of ionic migration is a real distillation, and Fenner believes, rightly, that the mineralizing process resulting from gas action takes place while the magma is still fluid.

In previous works (6, 11), it was demonstrated that the formation of acid magmatic residual solutions comes from a sequence of reactions produced by equilibria modifications arising from the accumulation of volatile elements and assimilation of "sial."

Equilibria reactions corresponding to the crucial point of magmatic evolution are represented by the following equations:

$$(1)\ 2NaAlSi_3O_8 + CaSiO_3 \rightleftarrows CaAl_2Si_2O_8 + Na_2SiO_3 + 4SiO_2$$
$$(2)\ 2KAlSi_3O_8 + CaSiO_3 \rightleftarrows CaAl_2Si_2O_8 + K_2SiO_3 + 4SiO_2.$$

At the start, solvent power of magmatic emanations is considerable, and its concentration of alkaline compounds determines (in basic or neutral rocks to be percolated), reactions from right to left of above equations. In the presence of $CO_2$ under pressure, ion-calcium migrates as soluble bicarbonate, as long as there is $CO_2$ in excess.

In the advanced stage of magmatic differentiation, however, accumulation of Fl, Cl, $CO_2$, $P_2O_5$ and $H_2O$ in status of dissociation, takes place within residual solutions. These elements, in the presence of $SiO_2$ and alkaline metasilicates, gradually acidify the magmatic solution.

In acid environments, stable minerals are: orthoclase, microcline, muscovite, biotite and quartz. The tendency of the process established by ascending migration of magmatic emanations is the substitution of minerals occurring in basic or neutral rocks, such as plagioclase, pyroxene, amphibole, calcite, dolomite, and others, for those constituting granitic rocks. In this manner, solutions become gradually less acid, so that in less deep zones they turn into hydrothermal solutions, likely to bring about metasomatic processes giving rise to vein deposits.

## METALLOGENETIC HYPOTHESES.

Scientific basis of metallogenesis was introduced by Daubrée, Scheerer and Élie de Beaumont over a century ago, and precisely in 1841. Up to this date, very little knowledge has been gained in this realm of thought, where researchers have advanced and retreated to the starting point.

In the historical background of knowledge on mineral deposits, some chapters of its advance stand out distinctly in its full significance. Take this renowned one, from a notable book: "Élie de Beaumont might well be called the father of our modern thought on the formation of mineral deposits. He was the first to show that most mineral deposits must be regarded as just one phase of igneous activity" (10). From Élie de Beaumont to De Launay (1893), we can solely refer to Van Cotta's achievement (1859), which is a systematic study of mineral deposits and an exegesis of sound concepts on genetics. He also gave greater accuracy to Élie de Beaumont's ideas, admitting at length the existence of metasomatic processes promoted by magmatic emanations, although he did not categorically assert that deposit-forming elements issued from igneous rocks. In 1893, the theory of ascending magmatic emanations charged with elements derived from deep seated origins was revived by De Launay.

Fundamental notions of mineralizing solutions of magmatic origin as held by Kemp (1901), Lindgren (1901), and Weed (1903), had long constituted the groundwork of French metallogenetic school. However, the conceptions of J. H. L. Vogt (1893), adopted in 1923 by J. E. Spurr and later modified, were those that provided the ground for our modern concept (10).

Demonstrating the order of crystallization of magmas, Alan M. Bateman (10, p. 46) shows in a concise way the principle supporting the dominant theory:

> . . . with the subtraction of the more basic minerals from the magma, the residual magma in general becomes progressively more silicic. Granitic residual magmas

are solutions rich in silica, alkalies and water; some of this may be squeezed out into fissures to form pegmatites. With basic magma, however, the residual magma may be rich in iron. Volatile substances or mineralizers, such as fluorine, boron, chlorine, and tin, concentrate in the mother liquors of silicic rest-magmas and may become tapped off to form pegmatite dikes rich in rare minerals.

With progressing crystallization *the final aqueous extracts gather the metals that originally were sparsely contained in the magma, along with the rare elements, the rare earths, and chlorine, boron, fluorine, hydrogen, sulphur, arsenic, and other substances.*

These mother liquors become expelled upon final crystallization and constitute the magmatic solutions that give rise to most economic mineral deposits. Consequently, they are a part of magma of particular interest to economic geologists.

Further on Bateman states:

The magma is the direct source of most of the materials of hypogene mineral deposits (p. 64).

In 1938, at the German Congress of Berlin, the author presented a metallogenetic hypothesis founded on the geo-chemical migration of certain elements. Goldschmidt, Peters, Noddack, Strock, and others had by then partly investigated the geo-chemical cycle of most elements, a study that was still progressing. Data were being divulged claiming the revision of misconcepts on the formation of mineral deposits regarded as of magmatic origin.

The concept contended by the dominant school accepted and scientifically discussed by Professor Paul Niggli in two memorable studies (1, 2), can be summarized as follows (1, p. 13):

Investigations of the processes of ore deposition have again and again resulted in comparisons with pegmatite consolidation and fumarole action, and if differences exist between the views laid down by J. E. Spurr in his latest work, and those adopted by J. H. L. Vogt, W. Lindgren and W. Emmons, they are of a qualitative nature. Spurr believes that for many types of ore formation the relationship to ortho-magmatic consolidation is the more pronounced, while the other authors incline to the view that fumarole actions and deposition from young thermal waters offer the closest analogy. A consideration of these two standpoints may be deferred to the systematic treatment of ore deposits given later in this book. Their essential agreement in general principle, however, *confirms the view that magmatic ore solutions are the normal residual solutions of a comprehensive process of magmatic consolidation. In this sense, Spurr's expression "ore magmas" may be unreservedly accepted, and indeed welcomed,* as indicating that ore deposition is a part phenomenon of magmatic differentiation.

Here we need to stress the apparently fundamental notion on which Niggli built and systematized the metallogenetic theory accepted by the majority of modern researchers. In actual facts, some researchers have questioned the existence of "ore magma." We, ourselves, have demonstrated the inconsistency of such an hypothesis (3), a self-proffered conclusion indeed, since no one person has ever registered direct or indirect evidence. If it is desired to check the existence of a concentration of mineral vein-forming metallic elements in magmatic residual magmas, it is merely necessary to re-examine the centers of magmatic activity of different geologic periods uncovered by erosion.

Thereupon we firmly believe that Spurr's "ore magma" is undoubtedly a flight of fancy. Petrogenetic investigations by several authors on the dif-

ferentiation of basaltic magma, reveal the possibility of formation of acid magmatic residue rich in hyperfusible or volatile substances. Thus, granophyres and rhyolites are formed by injections *ex-abrupto* of such magmatic residue, whereas certain pegmatoid rocks and aplites are produced by percolation in surrounding rock. In centers of magmatic activity where rocks were investigated, no unusual richness of ore-forming elements was located.

A concentration of hyperfusible components is unquestionably produced.

Niggli states:

> No doubt the presence of volatile components, which is of such fundamental importance for the formation of ore deposits, also exercises a decisive influence on the course of ortho-magmatic differentiation (1, p. 70) . . . we have recognized that the ascending solutions of pneumatolytic and hydrothermal character have a chemical composition that is compatible with the view that they are residual solutions of the magmas (1).

These are self-asserting, evidence-agreeing concepts, although the admission of the existence of "ore magmas" is by no means implied.

### INCONSISTENCY OF THE PREVAILING HYPOTHESIS.

The existence of a residual magma unusually rich in ore-forming elements, has not so far been ascertained even by indirect method. All known examples of residual magma emission, granophyric, granite-porphyric, rhyolitic, and so forth, appear singularly poor in metallic substances such as Pb, Zn, Cu, Au, Ag, Ni, Mo, W, Sn, Sb, Hg, rare earths, and others.

We must emphasize that, although pegmatites gradually approach their source, this is, the magmatic chamber progressively exposed by erosional effects, they become poorer in beryl, rare earths, tin, uranium, and other substances. Likewise, occurrences are recorded whose pegmatites appear either unusually barren, or even lacking such element-bearing minerals.

With an investigation of the process of the formation of both pegmatite and hydrothermal veins and also of the existence of elements scattered throughout sediments and metamorphic rocks, the concept of migration of these substances mobilized by the magmatic residual solution, will appear obvious. It should also be borne in mind that the reality of the substitution occurring jointly with the formation of most pegmatites has been demonstrated by several authors.

We have already shown the generality of the process of granitization of great Archeo-Proterozoic massifs, where gradual assimilation of heterogeneous complex of rocks occurs mostly by substitution (3). Solutions of magmatic origin, percolating through igneous, metamorphic and sedimentary rocks, cause dissolution and precipitation of mineral substances. Under the pressure of several hundred atmospheres, volatile elements of greater depths react with compound-forming metallic elements diffused in rocks, bringing them closer to the earth's surface. In zones of structural deformation, such solutions are canalized and channel along fissures, where a progressive fall in pressure and temperature occurs. Reaction of fluid-magmatic emanations (enriched with various elements leached in the lower zones), acting upon percolated rocks, carries on the metasomatic process either under pneumatolytic or hydrothermal conditions.

Precipitation of compounds in solution due to loss of gaseous solvent or to reaction of gaseous-liquid and solid (surrounding rock) phases, determines the formation of minerals along veins or dikes.

This concept of the formation of mineral deposits of magmatic origin was adopted because of the following considerations:

(1) In known centers of early magmatic activity displaying evolution from basic to granophyric and up to granitic phases, no evidence whatsoever has thus far been recorded of any concentration of ore-forming metallic elements.
(2) Geochemical researches by Goldschmidt, Noddack, Peters, Bulow, and others, revealed in sandy-argillaceous and calcareous sediments the presence of most elements found in vein deposits, and sometimes in greater proportion than occurs in eruptive rocks.
(3) In ancient metamorphic (meso and katazonal) formations, whose rocks are supposed to have resulted from shale, sandstone, limestone, and beds of gypsite, original accumulations are no longer to be found of syngenetic deposits retaining certain metallic compounds such as PbS, ZnS, CuS, $CaSO_4$ and others.

Therefore, let us survey these convincing reasons step by step.

Petrographic investigations on gabbros, dolerites and granophyres, undertaken at Mull in Scotland (4), gave rise to no revelation concerning concentration of metallic elements in residual magma (ore magma).

If we are to accept J. H. L. Vogt's hypothesis of the formation of granitic residual magma, granting due restrictions requested by the latest findings, "that granitic magma is the final product of a long series of differentiations in the rest magma direction," we shall conclude that the concentration of the substances forming vein mineral deposits, does not take place. In discussing Vogt's hypothesis, Shand writes: "The presence of interstitial micropegmatite composed of quartz and alkali-feldspar, in many diabases, has been held to support Vogt's contention." Several researchers, especially F. Walker, have proved that the micropegmatitic residue of diabase and gabbro is not a secondary product. In my paper (6), on the magmatic province of Roroimã, along the Brazilian-Venezuelan borderline, there was demonstrated the natural sequence of physico-chemical equilibria that form the micropegmatitic residue. P. Eskola (Shand, op. cit.) maintains as well that the initial process of granite formation must have either been the differentiation of sima, or of the basaltic layer of the earth's surface. H. H. Thomas and E. B. Bailey (4) clearly show that granophyric dikes were produced by the differentiation of a gabbroid magma. It must, therefore be admitted that granophyres, rhyolites, dacites, quartz-trachytes, in addition to granitic, pegmatitic and aplitic apophyses, are formed by the consolidation of magmatic residue produced by the differentiation of basic magmas.

As to the genesis of mineral deposits of magmatic origin, the theory relies on the same concept, together with a subsidiary hypothesis that metallic elements such as Pb, Zn, Cu, Sb, Au, Ag, Sn, and others, spread within the basaltic magma, accumulate into the residual magma owing to the formation

of soluble compounds holding volatile (hyperfusible) elements. In quartz-diabases or dolerites, as well as in quartz-gabbros, relative concentration of apatite is found only in interstitial micropegmatite, whereas one would expect common occurrence of sulphide compounds of Pb, Sn, Cu, Sn, Sb, As and other combinations of W, Sn, Ta, Nb, V, with O, Fe, Mn, Ca, Ti, rare earths, and so on, in agreement with the prevailing theory vouched by Professor Paul Niggli. The absence of concentration of such elements in granophyres, rhyolites and dacites is therefore one of the most decisive proofs against the "ore magma" theory. It is indeed strange that Niggli (1) has not pondered the question from this viewpoint, and adopted instead a metallogenetic hypothesis evolved from the modern leading school, systematizing it so as to make it a doctrine supporting his "natural classification of mineral deposits of magmatic origin."

It is well to note that this discussion does not refer to syngenetic mineral deposits of magmatic origin, but only to epigenetic ones.

## ACTUAL GEOCHEMICAL KNOWLEDGE CLAIMS A NEW HYPOTHESIS.

Latest geochemical advances, especially with respect to the migrating cycles of certain elements, widen still further the gap between the evidence and the obscure features of the dominant theory.

In this sense, data obtained by Goldschmidt (*7*), Noddack, Minami, and others, are indeed most suggestive.

(*1*) *Boron.*—Goldschmidt states (p. 405):

> auch sonst haben unsere Erkenntnisse über die Geochemie des Bors zu neuen geologischen Schlussfolgerungen geführt. Bisher hatte man die Gegenwart von viel Turmalin in metamorphen Sedimenten meist als Zeichen einer Bor-Zufuhr, vor allen durch Kontaktmetamorphose, gedeutest. Heute wissen wir, dass der normale Bor-Gehalt mariner Tonsedimenten ausreicht, um Turmalinmenge von 1–5 Gewichtsprozenten des Gesteins zu bilden. Die Gegenwart von Turmalin in metamorphen Gesteinen ist deshalb durchaus nicht in allem Fällen ein Beweis für pneumatolytische Zufuhr von Bor-Verbindungen. Die Borsäure, welche aus dem Meere in die tonigen Sediment gelangt ist, wird bei Vorgängen der Gesteinsmetamorphose in dem Minerale Turmalin Gebunden, welches chemisch und mechanisch sehr widerstandsfähig ist.

It must also be borne in mind that eruptive rocks contain little boron, which is quite the contrary to what occurs in most sediments.

Goldschmidt recorded these data (*7*):

| | | |
|---|---|---|
| (*a*) Eruptive rocks average | 0.0005–0.001% | $B_2O_3$ |
| (*b*) Paleozoic shale average | 0.01 | $B_2O_3$ |
| (*c*) Iron ore of marine sedimentation | 0.05 | $B_2O_3$ |
| (*d*) Limestone average | 0.001 | $B_2O_3$ |
| (*e*) Saline sediments (sea) | 0.1 | $B_2O_3$ |

Sea water contains 15 grams of $B_2O_3$ per cubic meter. Hence, the source of supply of boron for the formation of tourmalinic rocks (pneumatolytic contact metamorphism), is not magmatic, or, at least, the hypothesis that it derives from poorer formations is illogical.

(*2*) *Lithium* shows similar distribution, inasmuch as eruptive rocks contain 0.0065% of Li, whereas sedimentary ones show 0.013% of $LiO_2$.

The usual elements of the deposits of magmatic origin, as well as the rarer ones that are supposed to have accumulated in acid magmatic residue (granite and pegmatite), may also be examined. All following data are transcribed from Goldschmidt's work (8).

(*3*) *Beryl.*—Eruptive rocks average, 0.0005% BeO.
Shales average, 0.0015% BeO.

(*4*) *Rare Earths.*—The following table shows the distribution, in grams per ton, of rare earth oxides in sand-argillaceous sediments, according to analyses by E. Minami (8).

| $Y_2O_3$ | $La_2O_3$ | $CeO_2$ | $Pr_2O_3$ | $Nd_2O_3$ | 61 | $Sm_2O_3$ | $Eu_2O_3$ |
|---|---|---|---|---|---|---|---|
| 35.7 | 21.6 | 56.6 | 6.57 | 27.8 | — | 7.50 | 1.23 |
| $Gd_2O_3$ | $Tb_2O_3$ | $Dy_2O_3$ | $Ho_2O_3$ | $Er_2O_3$ | $Tu_2O_3$ | $Yb_2O_3$ | $Cp_2O_3$ |
| 7.33 | 1.05 | 5.13 | 1.39 | 2.83 | 0.23 | 3.03 | 0.75 |

(*5*) *Thorium.*—In argillaceous sediments of Europe and Japan, 0.001% (E. Minami).

(*6*) *Niobium.*—In eruptive and sandy-argillaceous sedimentary rocks, 0.002%.

(*7*) *Molybdenum.*—In basic eruptive rocks, 3 grams per ton.
Eruptive rocks average, 15 grams per ton.

(*8*) *Tungsten.*—In basic eruptive rocks, 24 grams per ton.
Eruptive rocks average, 69 grams per ton.

(*9*) *Uranium.*—In eruptive rocks, 0.0004%.

(*10*) *Copper.*—In 1924, F. W. Clarke and H. S. Washington calculated an average of 0.01% Cu in eruptive rocks. Analyses by Clarke and Steiger of 329 different average specimens of American eruptive rocks gave a figure of 0.093% Cu. Analogous data were checked in sandy-argillaceous sediments. Average analyses of 52 specimens of terrigenous "schlicks" (shallow sea), revealed 0.0128% Cu. Mississippi mud yielded one-half of such average, and deep sea red clay displayed a figure twice as great. Moreover, important sedimentary syngenetic deposits are known, such as those of Mansfeeld, Germany.

(*11*) *Zinc.*—According to Clarke and Washington, eruptive rocks contain an average of 40 grams Zn per ton, while Clarke and Steiger specify the figure of 51 grams per ton. N. H. Brundin (8) states that in certain sediments the content Zn average attains 1,000 grams per ton. Sphalerite has been proved to form syngenetic deposits in calcareous rocks of sedimentary origin.

(*12*) *Cadmium.*—Goldschmidt declares (8):

Bezüglich der Mengen und der Anreicherungsvorgänge des Cadmiums in Sedimentgesteinen sei erwähnt, dass Cadmium nicht selten im Phosphorite stark angereichert vorkommt, in Mengen bis etwa 100 g. Cd per ton, diese Anreicherung verläuft etwa parallel der Anreicherung des Zinks.

(*13*) *Mercury.*—Regarding eruptive rocks, Goldschmidt believes that 0.1 gram per ton should represent a fair estimate. In sandy-argillaceous sediments, however, Stock and Cucuel found far higher averages. Certain European shales attain as much as 0.5 gram of Hg per ton (8).

(*14*) *Germanium.*—While eruptive rocks contain an average 4 grams per ton, sandy-clayish sediments yield up to 7 grams of Ge per ton.

(*15*) *Lead.*—Clarke and Washington recorded in eruptive rocks 20 grams per ton and G. H. Hevesy, an average 16 grams per ton, while E. C. Sullivan found 70 grams per ton in deep sea red clay. Goldschmidt and H. Hormann specify 20 grams of Pb per ton of sandy clayish sediments, compared with 5–10 grams in calcareous rocks.

(*16*) *Arsenic.*—According to Clarke and Steiger, there exists 5.6 grams of As in a ton of eruptive rock. In marine sediments of the Atlantic Ocean, B. Fr. v. Bulow found 4 grams per ton.

(*17*) *Antimony.*—In bauxite and sedimentary iron ores, Goldschmidt found nearly 1 gram of Sb per ton.

## CONCLUSION.

Data herein transcribed will enable researchers to draw far reaching conclusions likely to solve the genetic problems of vein deposits.

In previous studies (3), the author contended that metallogenesis is nothing but a chapter of geochemistry; data now available are conducive to a still greater conviction regarding the truth of such a concept.

A painstaking investigation must be made of the distribution of elements lying within the different geologic formations. This would be of decisive significance. While eruptive and sedimentary rocks were investigated by means of spectrographic-optic processes developed by the quoted authors themselves, a systematic determination of metamorphic rocks, particularly those affected by deeper granitization, must, of course, be looked for and welcomed. Comparison of the averages of metals which constitute the mineral deposits of magmatic origin, contained in eruptive, sedimentary and metamporphic rocks, would yield additional and interesting evidence regarding migratory cycles of elements. Yet, although available data of this kind are still rather scarce, one can definitely challenge the existence of a natural process of magmatic differentiation leading to an exceptional concentration of elements such as Pb, Zn, Sn, Cu, W, Sb, and others, within the last magmatic residual solutions. Such a conception, instead of explaining and supporting the theory of "metallogenetic provinces," renders it incompatible with the genetic notion based on the "ore magmas." Evidently, if one considers a magma, free from influences of pre-existing geologic formations, and submits it exclusively to its own fate, that is, if it undergoes a physico-chemical

evolution in a "sealed chamber" under variances of temperature and pressure, one cannot reasonably expect that its magmatic residue will display, in whatever region affected by its activity, singular variations in the concentration of its constituent elements. In other words, inasmuch as there is no reaction exercised by the magmatic residue acidified by the concentration of hyperfusible and $SiO_2$ on the surrounding "sial," it follows that one cannot justifiably anticipate that paragenetic variations will ensue so pronounced as to force the admission of the theory of "metallogenetic provinces" as an immediate consequence.

We believe, with Niggli, that a magmatic chamber functions mostly as a distillating apparatus, its emanations determining a migratory process in the surrounding geologic formations. Granitization of considerable sedimentary massifs brings about, therefore, the dissolution of a great many metallic elements lying in the sediments, and their upward migration.

To demonstrate this idea further, let us take, for example, the average composition of pegmatite, according to A. Fersmann (9):

| O | Si | Al | K | Na | Ca | Fe | Mg | H |
|---|---|---|---|---|---|---|---|---|
| 48.7 | 34.5 | 7.7 | 4.75 | 2.4 | 0.7 | 0.4 | 0.1 | 0.1 = 99.35% |

| | | |
|---|---|---|
| Granite-pegmatite | Rare earth's average | 0.02% (A. Fersmann) |
| Sandy-argillaceous sediments | Do. | 0.0148% (E. Minami) |

According the the prevailing theory, rare earths should be found concentrated in pegmatites. Yet, the data above show that the average of the rare earths within sediments is quite close to that recorded of pegmatites. Local concentration of rare elements in pegmatites, that is, the formation of pockets rich in rare earth minerals, beryl, uranium, and others, reveals a deceptive average. The analytical Table II, however, gives the averages of virtually all elements of pegmatites.

One can infer thereby that sediments may indeed contain a higher content of certain rare elements, and even the substances that occur in greater quantities in pegmatites and pegmatite-granites, if one considers the volume of pegmatoid rocks as compared with that of sandy-argillaceous ones. If one considers the superficial distribution of sediments on the earth's crust, as compared with the crosswise arrangement of tabular or lenticular pegmatites vertically bounded by granites and hydrothermal deposits, the conclusion cannot be escaped that the sediments effectively hold a quantitative predominance of such elements as recorded in Table II. Likewise, a similar inference may be drawn from the consideration of vein deposits of hydrothermal formation, which are mineral masses of relatively smaller size than the extensive sedimentary deposits located in regions affected by magmatic activity yielding mineral deposits. Diastrophism, a primer of magmatic activity, results from geodynamic processes operating in geosynclines, where extensive and numerous sedimentary deposits have formed during one, or more, geologic periods. It follows that not only scattered elements, but also the compound-forming ones accumulated by selective precipitation and settling,

TABLE II.

DISTRIBUTION OF RARE AND OTHER ELEMENTS IN ROCKS.

| | (1) Granite-Pegmatite % | (2) Sedimentary % | (3) Eruptive % |
|---|---|---|---|
| Nb | 0.001 | 0.002 | 0.00003/0.002 |
| Th | 0.005 | 0.001 | 0.0016 |
| W | 0.001 | —— | 0.005 |
| Cs | 0.001 | 0.0007 | 0.0009 |
| Rb | 0.010 | 0.031 | —— |
| Zn | 0.002 | 0.010 | 0.004 |
| Cu | 0.001 | 0.006/0.025 | 0.093 |
| Sc | 0.001 | 0.048 | 0.0006 |
| Cl | 0.001 | 0.048 | 0.048 |
| Mn | 0.05 | 0.062 | 0.10 |
| Ti | 0.04 | 0.46 | 0.61 |
| Zr | 0.04 | —— | 0.029 |
| Mo | 0.01 | —— | —— |
| Rare earths | 0.02 | 0.0178 | 0.020 |
| F | 0.04 | 0.03 | 0.03 |
| C | 0.03 | —— | —— |
| Be | 0.03 | 0.0015 | 0.0005 |
| P | 0.10 | 0.07 | 0.08 |
| B | 0.10 | 0.05 | 0.0005/0.0003 |
| Li | 0.10 | 0.013 $Li_2O$ | 0.0065 |
| Sn | 0.011 | 0.004 | 0.0004 |
| Sb | —— | 0.0001 | 0.00022/0.0004 |
| Pb | —— | 0.0016 | 0.002 |
| U | —— | —— | 0.0004 |
| As | —— | 0.0004 | 0.00056 |
| Ta(4) | 0.002 | 0.001 | 0.00002 |

(1) From A. Fersmann, op. cit. (0.65% of granite-pegmatite's analyses).
(2) From A. M. Goldschmidt, Clarke and Washington.
(3) From A. M. Goldschmidt, Clarke and Washington.
(4) In Northeastern Brazil, mostly in the State of Paraíba, intense mining was lately conducted in pegmatites unusually rich in tantalates, revealing the existence of a tantalite proportion of 1:5.000, or 0.02% $Ta_2O_5$. It is therefore probable that average Ta in pegmatites does not exceed 0.001%.

are again mobilized and re-enter a new migratory cycle during the phases of distillation of the magma.

Syngenetic deposits of copper, lead, zinc, vanadium, sulphur (in gypsite, iron sulphides, and so on), directly or indirectly affected by magmatic residual solutions or its emanations, would appear to undergo the same metasomatic transformations to which the sediments were subjected when their formation took place. Hence, enormous volumes of sediments submitted to intense granitization, in the kata-zone, where metallic compounds are replaced by Na-Al, K-Al, Ca-Al, or Mg-Fe, silicates, would be liable to supply the greater part of vein-forming elements.

Percolation through sediments of volatile elements such as $H_2O$, F, Cl, $CO_2$, S ($H_2S$), As, and others, gives rise to both volatile and soluble compounds under physico-chemical conditions dominant in the kata- and meso-zones, compelling the upward migration of metallic compounds to the earth's surface, where geotectonic processes of displacement predominate. From

meso-zone to epi-zone, or zone of ruptural deformation, both magmatic emanations and their load of dissolved elements, in ionic status, are canalized along cleavages and fissures.

In 1938 (3), we stated:

Syngenetic deposits of galena, sphalerite, and copper compounds have been located. These deposits are, undoubtedly, not the privilege of any definite geologic period: hence, they could have formed in different periods of Archeozoic and Proterozoic sedimentation.

In several different countries such as Chile, Peru, Mexico, United States, and others, post-Tertiary magmatic activity affected extensive and thick sedimentary formations of diverse geologic periods. Mineral deposits formed in the Andes, as well as in the orogenic Mexican and North American formations, are well known.

Natural corollary from the metallogenetic concept hereby proposed, is the support granted to the theory of the "metallogenetic provinces." Of course, if the formation of mineral vein-deposits relies on elements scattered throughout sediments, then it only follows that, indirectly facies of regional sedimentation would affect the nature of these deposits.

In a previous publication (1938), I discussed certain features of the theory of migration of elements and precisely of those correlated with the formation of mineral deposits that occurred under the influence of magmatic emanations. At that time Goldschmidt divulged his work on the geochemical distribution of elements, which was an improvement of his previous investigation on the migratory cycles of elements. Hence, studying the formation of granitic-gneissic rocks, we stated (3, 13):

(1) That such rocks were formed by gradual metamorphism;
(2) That all known Brazilian granites (batholitic) are palingenetic;
(3) That granitization took place by the replacement of plagioclase and ferrous-magnesian minerals within pre-existing rocks, for microcline, quartz and muscovite;
(4) That the agents of the transformation are magmatic emanations;
(5) That magmatic emanations are not necessarily rich in metallic and metalloid deposit-forming elements;
(6) That magmatic emanations promoting the migration of constituent elements that enter in the composition of percolated rocks, take along other elements either in the status of combination and spread over, or fixed in accessory and rare minerals within, the same rock;
(7) That thus enriched with metallic and metalloid elements, magmatic emanations in fluid gaseous status infiltrate in the zone of ruptural deformation of the earth's crust, making possible the metasomatic processes yielding mineral vein-deposits.

Furthermore, for the solution of several paragenetic problems arising from the coexistence of typomorphus minerals of meso-zonal and epi-zonal conditions, we revised our own investigation of gold-veins in the State of Minas Gerais, and Hussak and Derby's as well, with the purpose of ascertaining the

concept of the "reincidence of mineralization" that had been contended by these two famous researchers. Superposition of metasomatic processes in the same fissures at different times, was indeed an ingenious solution for several physico-chemical questions correlated with the formation of mineral deposits of magmatic activity. In many a deposit one finds typomorphous minerals of pneumatolytic conditions lying side by side with others of hydrothermal formation. Geologists debate and discuss this problem up to this date, whereas the admission of a logical concept of mineralizing recurrence would decidedly elucidate the genetic record of vein deposits. Also, there should be mentioned the deposits of Passagem, Morro do Bule, and Bico de Pedra, in the municipality of Ouro Preto, and of Morro Velho, in Nova Lima, besides others in the State of Minas Gerais, where structural investigation reveals a definite distinction of two tectonic phases, which agree in full with findings by the geologic survey of Mid Minas Gerais, where Proterozoic formations are located.

As regards copper, nickel, iron, titanium, chromium, and the metals of the platinum group, it is known that they can form mineral deposits by magmatic concentration. Bateman writes (10):

> Certain accessory or uncommon minerals of magmas may become concentrated into bodies of sufficient size and richness to constitute valuable mineral deposits. Magmatic ore deposits are characterized by their close relationship with intermediate or deep-seated intrusive igneous rocks. Actually they themselves are igneous rocks whose composition happens to be of particular value to man. They constitute either the whole igneous mass, a part of it, or adjacent bodies. They are magmatic products that crystallize from magmas. They are variously termed magmatic segregation, magmatic injections, and igneous syngenetic deposits (p. 69).

It follows that these elements are trapped in basic rocks of foremost crystallization. Taking into account that their deposits belong to rock masses that invaded less deep levels of the "sial," they will consequently be subjected to the new magmatic processes which will take place in that region, resulting from a new diastrophic phase.

As recorded in sedimentary and metamorphic rocks, eruptive masses can be subjected to a more or less deep granitization; then, most elements will be mobilized by acid emanation and taken to higher geologic levels until a point is reached, where, influenced by metasomatic processes, they will precipitate into sulphides and other compounds.

Chromium migrates in hydrothermal alkaline solution, and imbues quartzite which produces the green rock termed prase, or infiltrates across schists and turns them into fuchsite-rich phyllites. Copper lies within veins in many sulphide compounds. Nickel occurs in pyrrhotite and other sulpho-arsenates.

As to platinum, a really noteworthy occurrence has been located 100 miles north of Belo Horizonte, State Capital of Minas Gerais, close to the locality of Morro do Pilar, along the stream of Limeira, in the municipality of Conceição do Matto Dentro. Algonkian (Itacolmí Series) formation in this area displays a quartzitic layer unusually rich in sericite. Microscopic research revealed the existence of several granite-pegmatite minerals such as xenotime, and a tantalum-niobate of uranium and rare earths, of pitch-black

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color. The quartzite rock is probably a diaphtoretic type, which is a granitized quartzite altered by hydrothermal metamorphism; and it yields nuggets of platinum and gold attaining sometimes 1 gram each in weight. Considering that the original sediment (quartzite) is not conglomeratic, it is unlikely that the metals accumulated in alluvium. Agreeing with the nature of the occurrence is the hypothesis that the platinum, affected by the same process that sericitized the granitized quartzite, migrated upward from a lower seated deposit.

Hussak (14) reported a similar occurrence of platinum and palladium with gold, not only in that region, but at Candonga as well. Up to that time, the origin of platinum yielded at Conceição do Serro was unknown, since investigations had been aimed at ultra-basic rocks which were regarded as the probable mother rock of platinum, and taking into account that the find had been fortuitous.

Instituts de Tecnologia Industrial
de Minas Gerais,
Belo Horizonte, Brazil,
*Sept. 15, 1947.*

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# REPORT OF COMMITTEE ON BASIC RESEARCH IN THE FIELD OF INDUSTRIAL MINERALS AND ROCKS.[1]

JOSEPH L. GILLSON AND RICHARD H. JAHNS.

In December 1945 the Council of the Society of Economic Geologists authorized the appointment of a committee to further research in economic geology, and in February 1946, this committee began to outline a program under the chairmanship of C. H. Behre, Jr. As pointed out in a recent issue of this Journal,[2] the principal fields of research in economic geology were judged to include ore deposits, coal, petroleum and related products, nonmetallics other than fuels, ground water, and engineering geology.

The Subcommittee for Research in Nonmetallics has been somewhat flexible in its membership and informal in its procedure. It currently comprises the following active members:

Oliver Bowles, U. S. Bureau of Mines (retired), Washington, D. C., U. S. A.
R. M. Foose, Department of Geology, Franklin and Marshall College, Lancaster, Pennsylvania, U. S. A.
J. L. Gillson, Geologist, E. I. Dupont de Nemours Co., Wilmington, Delaware, U. S. A.—Chairman.
R. H. Jahns, Division of the Geological Sciences, California Institute of Technology, Pasadena 4, California, U. S. A.
M. E. Johnson, State Geologist of New Jersey, Trenton, New Jersey, U. S. A.
T. L. Kesler, Geologist, Thompson-Weinman and Company, Cartersville, Georgia, U. S. A.
J. E. Lamar, Illinois State Geological Survey, Urbana, Illinois, U. S. A.
D. M. Larrabee, U. S. Geological Survey, Denver, Colorado, U. S. A.
E. F. Osborn, Division of Earth Sciences, Pennsylvania State College, State College, Pennsylvania, U. S. A.
H. S. Spence, Mineral Resources Division, Bureau of Mines, Canada Department of Mines and Mineral Resources, Ottawa, Canada.
R. E. Van Alstine, U. S. Geological Survey, Washington, D. C., U. S. A.

The primary objective of this group is a program of research, developed in the most informal manner consistent with effectiveness. The members hope to aid in planning and stimulating paths of research that seem to be in general the most desirable, but wish to avoid any suggestion of administering the research projects themselves.

Although there are many working definitions of the term "nonmetallics," the functions of the Committee are considered to extend over the field of the so-called industrial minerals and rocks only, and hence such nonmetalliferous

[1] Report of the Subcommittee for Research in Nonmetallics, Society of Economic Geologists. This is the fifth of a series of reports under the Committee on Research, Society of Economic Geologists, Charles H. Behre, Jr., Chairman. The field is taken to include all nonmetallics other than fuels.

[2] Behre, C. H., Jr., Society of Economic Geologists Research Committee: Econ. Geol., vol. 42, No. 5, pp. 505–509, 1947.

materials as coal, oil, and gas are excluded. It has been generally agreed that attention might best be further focused upon problems involving basic geologic research, rather than upon matters of processing and marketing. This hardly means that questions of beneficiation, recovery, and use should be or even can be ignored or avoided, as they constitute a significant, indeed vital part of the general program, but the Industrial Minerals Division of the American Institute of Mining and Metallurgical Engineers is an already well-established organization for the handling of such matters. It seems plain that concentration by the Society of Economic Geologists upon the most fundamental types of geologic inquiry, comprising principally the genesis, occurrence, and nature of industrial minerals and rocks, will involve the least duplication of effort and yield the greatest ultimate return of useful data.

The Committee, in planning its activities, hoped that it would be practicable:

a. To determine the current status of active research projects in the field of industrial minerals, particularly so far as programs of colleges, universities, and Federal and State bureaus are concerned.
b. To select from gaps in the known coverage of current research those further lines of investigation that show greatest promise, and to try to stimulate investigations along these lines at the various bureaus and research laboratories.

It has not been possible for the members of the Committee to meet as a single group at any time since its organization; nevertheless, an initial attempt was made, through the medium of correspondence, to develop a preliminary list of what were considered especially urgent and worthwhile problems for research. This list was briefly presented for discussion at the joint meeting of the Society and the American Institute of Mining and Metallurgical Engineers in New York during March 1947, even though it had not been possible at that time to formally canvass the numerous individuals and organizations engaged in research projects or sponsoring them. Fifty-one lines of possible research in the field of industrial minerals were suggested by sixteen interested persons, including members of the Committee, and were discussed by the Committee on one exchange of correspondence. The list presented was by no means considered a final one, but was intended merely to show some general trends of thought and to stimulate the membership of the Society to further suggestions.

The general field of industrial minerals and rocks is a difficult one to approach in a systematic manner. For example, classification of possible research projects by commodities is not wholly satisfactory, in part because some projects do not apply to specific commodities, and in part because neither commercial nor scientific interest in any one commodity is commonly very broad in scope. Notable exceptions to this are known, of course, but in general a specific problem in talc is rarely of compelling interest to the man engaged in studies of borax or beryl, just as a project that applies solely to building stone rarely will hold the attention of those working with fluorspar or bentonite. Such individual interests were well illustrated in the preliminary poll of opinion, when only four of the fifty-one lines of research were suggested by more than one person! The many diverse interests in the field

as a whole make any attempt to select research projects of general scope a difficult one, and this becomes a real problem, indeed, when the question of financing the research must be raised. The same general disadvantages apply to a single classification by usage, or by individual minerals.

The wide variety of research problems originally suggested and the trend of the subsequent discussions bearing upon these problems made it plain that the preliminary list could not be used as a basis for specific recommendations. None of the problems had had thorough consideration and discussion. Certainly not all of them, suggested as they were on short notice, could represent the most thoughtful judgments of those who suggested them. But most important was the obvious incompleteness of the list, in terms of areas and regions, commodities, and general types of problems represented.

In order to provide a fuller, more satisfactory basis for further discussions and interpretations, the list was expanded and much additional information was obtained by means of a questionnaire sent to geologists in the United States and Canada. Members of the Geological Society of America who reside in these two countries, who were nominated prior to 1945, and whose chief interests lie in fields other than petroleum geology, received copies of the letters. This means of selection was assuredly arbitrary, but seemed to be a workable way of limiting the number of queried persons while providing a reasonable coverage of the general field. Each man was asked:

1. What problem or problems of basic geologic research in the field of industrial minerals, in your opinion, merit particular attention at the present time?
2. What problems in this field are now under investigation by you or in your organization?
3. Have you a man or men seeking a research problem on which work could be undertaken in the near future, and have you funds available to finance it?

A total of 557 letters was sent out on May 19, and 82 replies were received by July 9. This represents a rather unimpressive batting average of .147, but does not seem solely attributable to lack of interest on the part of those questioned. Some of the men undoubtedly were in the field or were otherwise not readily accessible, some very likely have retired from active work in geology, and the interests of others may well have shifted to other fields of work during recent years. Perhaps a quarter or more of those who reasonably could be expected to answer such a questionnaire actually found time to come through with an answer. More than half of those who did answer expressed considerable interest in the Committee's work, and nearly all indicated a favorable disposition toward the announced objectives. One man frankly admitted to a growing impatience with questionnaires, suggesting with humor that it might "be better for all concerned if the various committees stopped meeting and did some research work on their own." Another opined that if funds and facilities were made available, the pursuance of research would take care of itself. Probably few persons would disagree with him on

the necessity for funds and facilities! Both men, it might be added, contributed several sound suggestions for projects.

Twelve men replied that the letter raised questions that were not in line with their current work or with work they have done during the immediate past, and four of these men referred the letter to others more qualified to reply. Three men have been retired for so long a period that they no longer consider themselves in touch with current questions in the field. Eleven others made no suggestions and added no comment. Single suggestions were advanced by thirty-five men, two suggestions by eleven men, and three or more by nine. Six men included published papers or documents in support of their ideas.

Twenty-one of those questioned indicated that no problems in the industrial minerals field are currently under investigation by them or by their organizations, but twenty-five others cited one problem, four two problems, and twelve listed three or more problems. These problems of course range widely in nature, scope, and location. Those under investigation by State and Federal organizations tend to be of more direct economic application than those holding the attention of many individuals and universities. The Federal Geological Survey is currently or has been recently concerning itself with soils, clays and other ceramic minerals, hydrous magnesium silicates, carbonate minerals, fluorspar, monazite and other heavy detrital minerals, corundum, talc, pegmatite minerals, and granite. The State organizations are devoting considerable attention to nonmetallic minerals of present and potential future commercial importance in the respective states. Thus several of the Southeastern states are investigating deposits of sillimanite, kyanite, sericite, vermiculite, muscovite, asbestos, corundum, topaz, olivine, kaolin, and talc, while the Northeastern states are currently much interested in talc, granite, limestones, salines, clays, and glacial deposits. Loess and loessial deposits, soils, clay minerals, limestones, glass sands, dolomite, salt, and fluorspar are being investigated in several of the Central states. Farther west are State-sponsored activities in light-weight aggregates, anhydrite, barite, pegmatite minerals, clay minerals, titanium minerals, limestone, glass sands, vermiculite, and potash deposits. It is evident from this partial list that the variety of projects is great, and that there is considerable overlapping from one part of the country to another.

The State and Federal organizations are not overlooking more purely scientific investigations, as both laboratory and detailed field work of this type are going forward. Some field work and a very large amount of laboratory work also are being done by numerous universities and by many private organizations throughout the country.

In connection with research problems that could be undertaken in the near future, thirty men reported that they had neither personnel nor funds available. One or more men but no funds could be supplied by thirteen others, and some funds but no men by only six. Eight organizations, comprising four universities, three State surveys, and one Federal agency, appear to be in the favorable position of having both men and at least some of the financing available for such projects. A detailed break-down of these replies

appears in the table below, but it should be remembered that this summary is far from complete. It includes the chief Federal agencies and most of the State agencies, but only a small proportion of the individuals and other agencies engaged in work in the general industrial minerals field.

All lines of research in nonmetallics other than fuels that have been suggested to date are included in the following list. Many are grouped by commodities, whereas others are of more general scope. They range from highly detailed investigations of specific minerals or of specific techniques to broad regional surveys of the type conducted in the Missouri River drainage basin by the U. S. Geological Survey. Further comments or discussions on any or all of them are earnestly solicited, either by correspondence with members of the Committee or by publication in this Journal.

POSSIBLE LINES OF RESEARCH.

*Aggregates:* Studies of deleterious minerals, colloids, etc. in concrete aggregates; correlation of undesirable constituents in aggregates with their source (involving, for example, detailed mapping of glacial deposits or of river-terrace gravels).

*Allanite and other uranium and thorium-bearing minerals:* Rescrutiny of geology, with new data on occurrence and prediction of distribution.

| | Federal agencies | State (or Provincial) surveys | Colleges and Universities | Private companies | Individuals |
|---|---|---|---|---|---|
| One problem under investigation | 2 | 10 | 11 | 1 | 1 |
| Two problems under investigation | 0 | 2 | 1 | 0 | 1 |
| Three or more problems under investigation | 4 | 5 | 3 | 0 | 0 |
| One or more men seeking problem, but no funds available | 0 | 2 | 10 | 0 | 1 |
| Funds to support, but funds not available | 1 | 3 | 1 | 1 | 0 |
| One or more men seeking problem, with part of funds available | 1 | 3 | 4 | 1 | 0 |
| Neither funds nor men available for new projects | 5 | 13 | 8 | 2 | 2 |
| Total reporting | 7 | 21 | 23 | 4 | 3 |

This summary represents only partial coverage of all organizations and individuals active in the fields of industrial minerals research in the U.S. and Canada. It is nearly complete for Federal agencies, and probably is at least somewhat representative for State surveys, colleges, and universities.

*Alunite:* Origin and relations to other deposits.

*Barium:* Geochemistry; new data on the geologic relations of barite.

*Bauxite:* General monographic treatment of the bauxitization and kaolinization problems.

*Bentonite:* Origin in relation to paleogeography and to deposition of volcanic glass; rate of alteration; fundamental properties, and tests to distinguish various types; relations of swelling and non-swelling bentonites.

*Borate minerals:* Restudy of stratigraphy and geology of borate deposits in the Southwestern states; further studies of borate mineralogy.

*Building stones:* Further studies in the problem of rock bursts; study of stability of pyrite and limestone and dolomite in relation to the weathering resistance of these rocks; general studies of igneous rocks used for building stones, involving detailed mapping and structural examinations; more accurate determination of durability and other commercially important characteristics, in terms of mineral and chemical composition.

*Cement:* Petrography of Portland cement clinker; further study of chemical reactions between cements and aggregates in concrete.

*Chromite:* Monograph on the geology of chromite.

*Clay minerals:* Further studies on the conditions of formation; studies of base-exchange phenomena; genesis and mineralogy of high-alumina clay deposits and associated rocks; relations of clays to adjacent deposits; extension of basic mineralogic research on clays, and correlation of mineralogic data with physical and industrial properties.

*Corundum:* Origin and occurrence of deposits; correlation of these data with types of corundum; evaluation of commercial possibilities of natural versus synthetic corundum.

*Dolomite:* Monographic treatment of the problem of dolomitization; detailed studies of minor variations in dolomite deposits.

*Fluorine:* Geochemistry of fluorine; recovery of fluorine from fluophosphates.

*Fluorspar:* Monograph on the geology of fluorspar deposits, including all non-commercial types.

*Glauconite group of minerals:* Paleogeography and origin.

*Glass sands:* Problems of sedimentation in connection with development of glass sands and other specialized sedimentary rock types.

*Gravel:* Geology of gravel deposits, classified according to genesis; more accurate correlation of structures and textures with conditions of sedimentation.

*Gypsum and anhydrite:* Relation to dolomite; interrelations of gypsum and anhydrite.

*Magnesite:* Origin and further classification of magnesite deposits, preferably based upon detailed mapping and structural and petrographic studies.

*Light-weight aggregates:* Studies of volcanic materials (cause of exfoliation in perlites, etc.).

*Loessial materials:* Physical and chemical properties; detailed tracing of changes from diagenesis to final deterioration into clay.

*Monazite:* Careful rescrutiny of geology of monazite deposits; occurrence and detailed mineralogy.

*Olivine:* Systematic studies of occurrence of dunite deposits, studies of variations in olivine content of dunite masses.

*Pegmatite minerals:* Integration of all data on feldspar deposits, with special reference to their distribution within pegmatites and pegmatite districts; similar studies of other pegmatite minerals, particularly those not investigated in detail by the U. S. Geological Survey during the past eight years; monograph on the geology of pegmatites; careful scrutiny of all pegmatites

as possible sources of beryllium, with studies of beryllium-bearing minerals other than beryl.

*Phosphate deposits:* Monograph on geology and mineralogy of phosphate sources, including non-commercial types; relations between phosphorus and vanadium in Idaho and Wyoming deposits.

*Potash deposits:* Further studies of occurrence and geologic relations; distribution of sylvite and other potash minerals in salines.

*Pyrophyllite:* Occurrence and origin, in contrast to talc.

*Salt:* Detailed stratigraphic and petrologic studies; further studies of chemical composition.

*Serpentine:* Restudy of the serpentinization problem, with accumulation of new data from all parts of the country.

*Sillimanite, kyanite, andalusite, and dumortierite:* Further studies of occurrence.

*Soda ash:* General study of soda-ash deposits of the United States.

*Sulphur earths:* Agricultural properties in terms of detailed mineralogy.

*Talc:* New investigations on the genesis of talc deposits, with reclassification of occurrences on a genetic basis; relations of talc deposits to areal and structural geology; physical and chemical properties of steatite in connection with adaptablity for electrical uses.

*Titanium minerals:* Mineralogy of complex ores; monograph on geology of ilmenite and ilmenite deposits, especially those in the United States.

*Vermiculite:* Detailed studies of geologic features of vermiculite deposits, and correlations with specific properties of the mineral.

Areal mapping of selected regions, in terms of such specific problems as mineral zoning, localization of ore bodies with respect to structural, stratigraphic, and other features, wall-rock alteration, and sources of mineralizing solutions.

Detailed mapping in vicinity of nonmetalliferous deposits, and more detailed mapping of the deposits themselves.

General sedimentation studies, in terms of development of sand and gravel deposits; includes deposition by ice, wind, and water.

Studies of accessory minerals in beach and dune deposits.

Studies of granite, syenite, and other igneous masses as potential sources of certain minerals, based on bulk treatment.

Further pursuance of trace-element studies.

Equilibrium studies at elevated temperatures and pressures, in both hydrous and anhydrous systems.

Transfer of $SiO_2$ by water in the supercritical state.

Experiments on the synthesis of such minerals as diamond, mica, quartz, asbestos, and vermiculite.

Studies of recrystallization and reaction rates, under directed or hydrostatic pressure, and with or without volatile components.

Geology of ocean bottoms.

Studies of thickening and thinning of beds during folding, with relations to the opening angle of a given fold; determination of the mechanics of material transfer.

Studies of porosity of nonmetallic minerals.
Correlations between types of deposits and type of country rock, wall-rock alteration, and structural environment.
Zoning of nonmetalliferous deposits.
Laboratory studies of inclusions in minerals.
Studies of nonmetallic mineral genesis, approached from the standpoint of source and direction of mineralizing solutions (including studies of asymmetrical crystals, composite crystals, etc.).
Further development of geophysical and geochemical techniques for the prospecting of nonmetallic deposits.
Further development of spectrographic techniques for determination of minor constituents of rocks and nonmetallic minerals.
Development of regional surveys of nonmetallic mineral resources, similar to that conducted in the Missouri Valley basin by the U. S. Geological Survey.
Detailed studies of variability of physical and chemical properties of such minerals as dolomite, clays, etc.
Development of a systematic program for the collection of geological information at depth, to be obtained from wells, borings, and other excavations for water, oil, salt, limestone, or gypsum.

The list is a long one, in part because the field of industrial minerals and rocks is expanding rapidly, and in part because many of the items are of compelling interest to only small segments of the geological fraternity. The list is also a heterogeneous one, but most of the suggested problems can be classified in a rough way according to whether they place emphasis upon field mapping; petrologic and structural studies (including sedimentation and other specialized fields); geochemical and geophysical studies; compilation, correlation, and interpretation of existing data; or upon certain specialized approaches.

Perhaps E. N. Callaghan put a finger upon the most fundamental geologic need in the nonmetallics field when he strongly recommended field work as intensive as that applied to metalliferous deposits in the past. This thought was echoed in various forms by several other geologists. Repeated suggestions also were made for additional intensive work on mineral synthesis, further development of spectrographic techniques, and other laboratory projects, whereas many others—more specific in nature—dealt with clay minerals, fluorspar, limestone, light-weight aggregates, monazite, and uranium-bearing minerals.

As a result of all discussion to date, and in terms of all data currently at hand, the Committee suggests ten lines of research as a tentative "top-priority group." This we do with full awareness of an incomplete set of basic data, the possibility of a considerable sampling error in our poll of geologists, and the difficulties in obtaining the best possible collective judgment among these geologists. The differences of opinion are great, and the consulting of additional geologists undoubtedly would introduce still different points of view. The list therefore should not be regarded as fixed, but merely as one of currently preferred projects that is subject to revision at any time. At present,

however, it contains those projects of fundamental nature that appear to offer the greatest promise for adding to our knowledge of industrial mineral deposits.

1. Detailed mapping, structural analysis, and petrologic study of individual deposits.
2. Detailed areal mapping of selected regions, particularly those in which deposits of industrial minerals are abundant. Such work might involve the mapping of bed rock, of surficial deposits, or of both.
3. Sedimentation studies, aimed at a fuller understanding of the genesis of water-, wind-, and ice-laid deposits.
4. Experiments on the synthesis of minerals.
5. Equilibrium studies at elevated temperatures and pressures.
6. Further development of spectrographic techniques, particularly those for quantitative determinations of minor constituents in minerals and rocks.
7. Additional studies of the clay minerals.
8. Additional studies of monazite and monazite deposits.
9. Further vigorous pursuance of trace-element studies, particularly for correlation of rocks, the accumulation of general geochemical data, and for the development of new prospecting techniques for nonmetalliferous deposits.
10. Studies on the zoning of nonmetalliferous deposits.

The above lines of research are by no means independent of one another, and interrelations may well be the rule rather than the exception. Further, studies in any one of these fields probably will lead to the accumulation of data bearing on other problems included in the previous, more extensive list. Thus, carefully planned areal mapping and the detailed mapping of individual deposits might well lead to important correlations between types of deposits and types of country rock, wall-rock alteration, structural environment, or other features.

Numerous specific comments on the above lines of research could be made at this time, but it seems more desirable to defer such comment until there has been opportunity for more complete discussion. Research in certain phases of these projects already is underway, and those persons engaged in such work might well be able to contribute many helpful suggestions and criticisms. Moreover, it is hoped that summary statements on each of the subjects can be prepared by appropriate geologists and published in this Journal. Such statements would be effective in disclosing the most desirable specific subjects for research, in terms of past and current activities of this and other countries.

The Committee wishes to thank all those whose interest in industrial minerals research prompted them to contribute information and suggestions. It has been impossible, thus far, to extend thanks or to answer all questions and points of discussion individually, but it is hoped that this will in no way stop any further suggestions.

## FINANCING RESEARCH.

Many organizations have funds and men available for research, and suggestions concerning reasearch problems to the directors of such organizations may be welcome, provided the projects submitted are sound and worthy, and of a type befitting the energies and facilities of the particular organization approached.

Although a few organizations have funds and no men available, the more general situation is the reverse—where competent men are available at Universities and Colleges, but the institutions lack the funds to carry on research commensurate with the abilities of the men, and with the laboratory facilities available.

In fact, the caliber of the technical men in the rising generation is most gratifying to the older generation of scientists. Many of these, not excepting some on the sub-committee itself, remember periods of frustration when their own abilities were handicapped by lack of funds for research. The poignant memory of those days stimulates the hope that this more able younger generation will not be so frustrated and handicapped. Their loss is individual and personal, the country's loss is real and irreplaceable—it must not occur.

Fortunately, some funds are available by such organizations as the Geological Society of America, and in the new National Science Foundation. Although applications for these funds will always be legion, it is obvious that applications that can expect favorable consideration must be ones that have received careful consideration, and are backed by men and organizations of recognized standing in the scientific world.

The Committee has selected these ten subjects that seem to be preferred by a cross-section of American geologists. Now it wants to aline competent research men to each of these subjects. Having the subject and the men, the Committee can go after the money. No promise is made that money will be forthcoming immediately, nor necessarily in adequate amounts. Nevertheless, applications for funds cannot be made until the subjects, the men, the laboratories and facilities are selected.

Obviously, each subject requires limitations set to the capacities of the men and facilities available, with goals aimed within time limits of reasonable lengths. Although the Committee feels that its own membership is competent to make these selections and limitations, it wants continued advice and stimulation from the geologists of the country.

# REVIEWS

**Origin and Development of Craters.** By T. A. JAGGAR. Pp. 508; plates 87; figs. 14. Memoir 21, The Geological Society of America, Baltimore, Md., 1947. Price, $6.00.

This very interesting volume, by a well-known volcanologist, shows the evolution of craters in the light of modern volcanology, as expressed by the twentieth-century activities of Kilauea Crater, as a type vent. It is divided into 7 parts.

Part 1, Kilauea Crater, 1912–1913, relates detailed and weekly observations made when the new volcano observatory was founded. Although the volcano has been quiet since 1913, Dr. Jaggar has tried to maintain the public's interest in it and to show that it is always undergoing physical changes, interesting for observation and study.

Part 2, Kilauea and Mauna Loa, 1909–1935, tells about the volcanic events at all the Hawaiian craters and their extensions in rift cracks during that period, with first-hand experimental measurements, adventures in gas collection and the influence of volcanic events on scientific work.

Part 3, Kilauea Steam Blast Eruption in 1924, is a sequence of minute-to-minute observations, night and day, by a dozen professional and volunteer observers who were looking down at the inner pit of an explosive eruption. It summarizes the evidence for correlation of tilt with tumescence and subsidence.

Part 4, Series of Development Sketch Maps and Profiles of Halemaumau, Checked by Topographic Mapping, 1917–1934, is explained year by year. The author has tried to make more intelligible the relationship between aphrolith (crag lava) and dermolith (lake lava).

Part 5, Hawaiian Crater Histories, starts with a bibliography of crater history in the Volcano Letter and the Hawaiian Volcano Observatory between 1913 and 1929. By telling the history of the Hawaiian volcanoes, their cycle is explained.

Part 6, Principles of Crater Evolution, reviews studies of volcanic vents in the nineteenth century by well known authors, and some more recent studies. It includes crateral physics and chemistry, as well as speculations on the circular symmetry of some lines of volcanics, with the statement that the driving forces are not only steam, but that the responsible gases are magmatic on one hand, and from contamination by surface water on the other. Volcanism is mostly submarine and most magmatic volcanism is submarine intrusion.

Part 7, Summary and Conclusions, shows that seismology is intimately correlated to observational volcanology and that the solar matter (H, C, N and O) under the bedrock of ocean bottom is fundamental in controlling the outflow of energy. Although Kilauea is the most quoted example by protagonists of the magma theories, there is still a lot of unknown due to its extension under the sea.

Some parts of the book are based on daily notes made on trips by the author who was at that time Director of the Hawaiian Volcano Observatory; all the experiences have really been lived. It is also noteworthy that it reproduces for the first time the Record Book of the Hawaiian Volcano Observatory.

All the illustrations are good; the plates have detailed descriptions in order to serve as graphic narrative and to supplement the text. The photographs are excellent and the ones taken during the explosions and at night are particularly impressive.

Geologists should gain a lot by reading this book; Hawaii being a typical example, they can take it as a basis for further and broader studies of other volcanoes. For the layman there can be much learned by it too.

M. L. MIGNONE.

**Memorandum sobre los Problemas de la Industria Minera de Bolivia (Memorandum on the problems of the Bolivian Mining Industry).** By CARLOS V. ARAMAYO. Pp. 91. Buenos Aires, June 1947.

This pamphlet was written while the author was exiled in Argentina; its purpose is to present to the general public, in non technical language, a view of the mining industry in Bolivia, and more particularly of its difficulties.

The geography of Bolivia is in itself a difficulty for mining: a table-land, high of access, an unfavorable climate, no access to the sea and the dangers of landslides and torrents. As if that were not enough, the Government which was in power until the revolution of July 1946, according to the author, undermined the industry by all sorts of measures: exhorbitant taxes, inflation, no security of rights, contradictory laws. Yet the mining industry—especially tin—is the backbone of the Bolivian economy, in fact it constitutes 80 percent of it. Being a "wasting asset," it constantly needs capital for new machinery, experiments, and prospecting of possible deposits. But with the then existing unstable situation no foreign enterprise wanted to invest in Bolivia, specially after a few discouraging experiences. Among other disadvantages this led to a lack of foreign exchange which might be needed for foreign purchases in case of emergency.

The information contained in this booklet is authoritative since the author is one of the big three tin miners in Bolivia. He suggests remedies to the situation, such as the constitution of a Special Commission, the creation of more large enterprises, a reduction of the bureaucracy and of the Army budget, which is out of proportion with the size of the country. He expresses hope for the future of the Bolivian mines if the new government takes the necessary measures and if the United Nations offers national security and free exchange.

M. L. MIGNONE.

**When the Oil Wells Run Dry.**—By WALTER M. FUCHS. Pp. 447; figs. 79. Industrial Research Service, Dover, N. H., 1946 (1947). Price, $4.50.

This interestingly written book is a story of oil in plain everyday language. It tells what oil is, where found, how formed, and how it is refined and used.

Chapter 1 is an interesting history of oil, its ancient uses and legends, and the development of the modern oil industry. Chapter 2, called the Haves and the Have-nots, deals with the occurrence, drilling, distribution, and oil politics. Chapter 3 takes up the United States industry in its various phases, including the people concerned with its development. Chapter 4, called, When the Oil Wells Run Dry, deals with the treatment of wells, oil prospecting and United States foreign interests. Chapter 5, Oil Man's Partner, reviews the chemistry of oil, refining and petroleum products. Chapter 6, Man-made Petroleum, is the story of coal and synthetic petroleum and the research involved. Chapter 7, The Wave of the Future, deals with the outlook for future sources of energy.

The book is interesting reading for the geologist and everyone interested in petroleum and the petroleum industry.

**Colloid Science, A Symposium.** By E. K. RIDEAL, Editor. Pp. 208; figs. 32. Chemical Publishing Co., Brooklyn, N. Y., 1947. Price, $7.00.

This volume is based on a postgraduate course sponsored by the Department of Colloidal Science, Cambridge University, under the auspices of the Royal Institute of Chemistry. It deals with disperse systems and the interpretation of the phenomena of surface films and interfaces. The various contributions are: Surface Chemistry and Colloids, by A. E. Alexander; Thermodynamics and Colloidal Systems, by D. D. Eley; The Study of Macromolecules by Ultracentrifuge, Electrophoresis, and Diffusion Movements, by P. Johnson; The Viscosity of Macromolecules in Solution, by F. Eirich; the Kinetic Theory of High Elasticity, by R. F. Tuckett; Emulsions *in Vivo*, by J. H. Schulman; The Study of Colloidal Systems by X-ray Analysis, by M. F. Perutz; Membrane Equilibrium, by G. S. Adair; Infra-red Spectra and Colloids, by G. B. B. M. Sutherland; Vinyl Polymerization in the Liquid Phase, by R. R. Smith.

The broad coverage of colloidal chemistry in this book is of chief interest to chemists, physicists, and biologists, but the subject is of growing importance in geology and will repay reading by geologists.

## BOOKS RECEIVED.

ALAN T. BRODERICK.

**U. S. Department of the Interior—Geological Survey.**

**Prof. Paper 210–E. New Upper Cretaceous Fossils from Mississippi and Texas. Part 1, Fossils from two Deep Wells in Mississippi. Part 2, A new Venericardia from Uvalde County, Texas.** By L. W. STEPHENSON. Pp. 35; pls. 3. Washington, 1947.

**Prof. Paper 211. Studies of some Comanche Pelecypods and Gastropods.** By T. W. STANTON. Pp. 256; fig. 1; pls. 69. Washington, 1947. *89 new species and varieties of gastropods and pelecypods described. Washita age of Devils River Limestone emphasized.*

**Bull. 944–B. Lead-Silver Deposits of the Clark Fork District, Bonner County, Idaho.** By A. L. ANDERSON. Pp. 80; pls. 9; figs. 2. Washington, 1947. *Fillings and replacements along low-angle thrusts and steep reverse faults in Belt series rocks—similar to Coeur d'Alene district, but smaller, higher grade.*

**Bull. 953–C. Aluminous Lateritic Soil of the Sierra de Bahoruco Area, Dominican Republic, W. I.** By S. S. GOLDICH and H. R. BERGQUIST. Pp. 31; figs. 3; pls. 5; tbls. 7. Washington, 1947. *6 million long tons, 44.2% $Al_2O_3$, 20% $Fe_2O_3$ estimated. Pliocene (?) deposits on very low-alumina-bearing Eocene limestone. Igneous source material of intermediate composition inferred from analyses.*

**Bull. 955–A. Drill-Hole Correlation as an Aid in Exploration of Magnetite Deposits of the Jersey Highlands, New York and New Jersey.** By H. E. HAWKES and P. E. HOTZ. Pp. 17; pls. 2; figs. 3; tbl. 1. Washington, 1947. *Stratigraphy techniques applied to stratiform metamorphics. Good check-off system of core logging.*

**Bull. 957–A. Geophysical Abstracts 128, January–March 1947.** By V. L. SKITSKY. Pp. 56. Washington, 1947.

**Bull. 957–B. Geophysical Abstracts 129, April–June 1947.** By V. L. SKITSKY. Pp. 60. Washington, 1947.

**Water Supply Papers.**

**866–C. Geology of Dam Sites on the Upper Tributaries of the Columbia River in Idaho and Montana. Part 3. Miscellaneous Dam Sites on the Flathead River Upstream from Columbia Falls, Montana.** By C. E. ERDMANN. Pp. 100; figs. 3; pls. 15. Washington, 1947.

**992. Bibliography and Index of Publications Relating to Ground Water Prepared by the Geological Survey and Cooperating Agencies.** By G. A. WARING and O. E. MEINZER. Pp. 412. Washington, 1947. *Annotated.*

**998. Suspended Sediment in the Colorado River, 1925–41.** By C. S. HOWARD. Pp. 165; fig. 1; tbls. 25; pls. 3. Washington, 1947. *Concentration depends more on source of increase than on amount of increase. Greatest variations caused by rains on desert parts of watershed.*

**1020. Water Levels and Artesian Pressure in Observation Wells in the United States in 1944. Part 5. Northwestern States.** By A. M. SAYRE AND OTHERS. Pp. 195; figs. 5. Washington, 1947. *Water levels and artesian heads given in reference to local land-surface datum planes.*

**Mineral Resources of the Belgian Congo and Ruanda-Urundi.** By the FOREIGN MINERALS DIVISION. Pp. 95; figs. 3; maps 11; tbls. 36. U. S. Bureau of Mines, Vol. 2, No. 6, Washington, 1947. *Valuable report giving economic background and audit of mineral potentialities. Compiled from all available data.*

**Geology of the Kramer Borate District, Kern County, California.** By H. S. GALE. Pp. 53; figs. 4; pls. 3. State Mineralogist's Report, Vol. 42, No. 4, San Francisco, 1946. *Up to 250 ft. thick lens of native borax and kernite surrounded by lower grade colemanite and ulexite. Result of evaporation of boron-bearing volcanic waters with concurrent overflow loss of other elements in Miocene basalt basin.*

**State Geological Survey of Kansas, Oil and Gas Investigations—University of Kansas Publications.**

**Preliminary Cross Section No. 3. Subsurface Geologic Cross Section from Ford County, Kansas, to Dallam County, Texas.** By F. C. EDSON. Pl. 1. Lawrence, 1947. *Horiz. scale 1" = 6 mi.; vert. scale 1" = 200'. Logs of 8 wells.*

**Preliminary Cross Section No. 4. Subsurface Geologic Cross Section from Scott County, Kansas, to Otero County, Colorado.** By J. C. MAHER. Pp. 11; section 1. Lawrence, 1947. *Paleozoic stratigraphic units correlated by microscopic examination of rotary cuttings and electric logs from 8 wells. Horiz. scale 1" = 6 mi.; vert. scale 1" = 200'.*

**Illinois Geological Survey.**

**Press Bull. No. 55. Developments in Illinois and Indiana in 1946 (Oil and Gas).** By A. H. BELL and R. E. ESAREY. Pp. 9; tbls. 8; fig. 1. Urbana, 1947.

**Circ. No. 130. Designs for Oil Field Tools to aid in Water Flooding.** By FREDERICK SQUIRES. Pp. 4; figs. 3. Urbana, 1947. *Three ingenious tools described; a shot-hole caliper, a shot-hole core drill and an automatic measuring and regulating water valve for inter-sand flow.*

**Engineering Experiment Station News.** Pp. 68; figs. 39; tbls. 11. Vol. XIX, No. 2. University of Ohio, Columbus, 1947. *Mainly non-technical articles on Ohio's mineral resources. Data on underground natural gas-storage, gasification of coal beds.*

**The Geology of the Flora Quadrangle, N. Dakota.** By J. R. BRANCH. Pp. 35; figs. 5; topog. map colored, 1/62,500; geol. map, not colored, 1/62,500; tbls. 3. N. Dakota Geol. Survey Bull. 22. Grand Forks, 1947. *Present surface and drainage is consequence of a set of recessional moraines with their outwash and ground moraine belts.*

**Publications on the Geology and Mineral Resources of Virginia.** By ARTHUR BEVAN. Pp. 58. Geol. Survey of Virginia, Circ. 6. University, 1947.

**Relation of Geology to Mineralization in the Morton Cinnabar District, Lewis County, Washington.** By J. H. MACKIN. Pp. 47; figs. 13; pls. 2. Dept. of Conservation and Development, Div. Mines and Mining, Report No. 6. Olympia, 1944. *Total production 5,000 flasks. Known reserves small. Cavity fillings in fault breccias, porous sandstones.*

**A Geologic Interpretation of the Failure of the Cedar Reservoir, Washington.** By J. H. MACKIN. Pp. 30; figs. 9. University of Washington Engineering Experiment Station, Bull. No. 107. Seattle, 1941. *Puget glacier moved* UP *Cedar Valley, deposited porous fluvatile gravel blockade near its front, impervious silts in lake farther upstream. Concrete dam in post-glacial rock-walled channel by-passed through gravel.*

**Soil Survey of Snohomish County, Washington.** By A. C. ANDERSON AND OTHERS. Pp. 76; tbls. 8; pls. 3. U. S. Dept. of Agriculture, Series 1937, No. 19. Washington, D. C., 1947. *3 physiographic divisions; (1) recent alluvial, (2) glacial ground moraines, outwash plains and terraces, (3) mountains.*

**Convection Patterns in the Atmosphere and Ocean.** By R. B. MONTGOMERY AND OTHERS. Pp. 138; pls. 15; figs. 38; tbls. 12. Annals New York Acad. Sci., Vol. 48, Art. 8. New York, 1947. *Presentation of latest work results, advanced theory, on convective layers. Formulae probably applicable to some geologic problems, e.g. magma convection.*

**Achievements in Optics.** By A. BOUWERS. Pp. 135; figs. 64. Monographs on the Progress of Research in Holland, No. 1. Elsevier Pub. Co. Inc. New York, 1946. *New developments of Schmidt camera principle (spherical mirror, correcting lenses) result in new camera, telescope, microscope designs. Phase retarding and absorptive rings added to standard microscope objectives increase definition of transparent bodies.*

**Annual Report of the Uganda Protectorate Geological Survey Department.** By K. A. DAVIES AND OTHERS. Pp. 25; tbls. 2. 1942. *Field and headquarters work by staff geologists, topographers.*

**Plane Table Notebook, with Plane Table Notes in Pocket.** By KENNETH K. LANDES. 2nd Edition. George Wahr Publishing Co., Ann Arbor, Mich., 1947. Price, $2.00 (wholesale, $1.60). *Stadia traverse blank note sheets, plane table notes describing methods, and blank coordinate sheets.*

**Brasil: Divisão de Fomento da Produção Mineral.**

**Avulso 69. Mica Lavra do Pequerí, Bicas, Minas Gerais.** (The Mica Deposit of Pequerí, County of Bicas, Minas Geraes). By M. R. KLEPPER, D. M. LARRABEE and A. L. M. BARBOSA. Pp. 34; tbls. 7; map 1. Rio de Janeiro, 1945. *Small transgressive zoned pegmatite in micaceous gneiss.*

**Avulso 71. O Código de Minas e o Incremento da Mineração no Brasil, 1942–1943 (List of Mines and the Increase of Mining in Brazil).** Pp. 77; tbls. 17. Rio de Janeiro, 1945.

**Avulso 73. Tantalita e Berilo em "Alto" Feio e Serra Branca, Estado da Paraíba (Tantalite and Beryl in the Feio and Serra Branca Mines, State of Paraíba).** By S. C. DE ALMEIDA. Pp. 26; maps 2; tbls. 3. Rio de Janeiro, 1946.

**Avulso 74. Pegmatito Tantalífero de Boa Vista, Paraíba.** By F. MOACYR DE VASCONCELLOS. Pp. 27; figs. 2; tbls. 2. Rio de Janeiro, 1946. *Replacement pegmatite in quartzites. Small reserves.*

**Avulso 75. Bismuto, Cobre e Ouro na Borborema.** By P. A. M. DE A. ROLFF. Pp. 36; photos 12; tbls. 3; figs. 5; map 1. Rio de Janeiro, 1946. *Small production of Bi, Au from pegmatites, tactites and their placers. Traces Cu.*

**Bol. 79. Relatório da Diretoria 1945 (Annual Director's Report).** By A. I. ERICHSEN. Pp. 202; tbls. 38; photos 16; maps 7; figs. 5. Rio de Janeiro, 1946.

**Bol. 80. Reservas Minerais do Município de Picuí.** By P. A. M. DE A. ROLFF. Pp. 52; tbls. 16; photos 23; figs. 4; maps 4. Rio de Janeiro, 1946. *Pegmatites, tactites, placers. Main reserves in Beryl and Tantalite.*

**Nota Preliminar sôbre a Jazida de Barreiro, Municipio de Araxá, Minas Gerais (Preliminary Report on the Barreiro Deposit, District of Araxá).** By DJALMA GUIMARÃES. Pp. 43; maps 2; photos 10. Instituto de Tecnologie Industrial, Avulso 2, Belo Horizonte, 1946.

**Estudos, Notas e Trabalhos do Serviço de Fomento Mineiro.** Pp. 69; figs. 6; photos 15; maps 2. Direcção Geral de Minas e Serviços Geológicos, Vol. 2, Fasc. 2, Lisbon, 1946. *Descriptions of residual and transported clay deposits, cassiterite-bearing pegmatites and placers.*

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# SCIENTIFIC NOTES AND NEWS

E. F. FITZHUGH, JT., has resigned his position as chief of the Minneapolis Division, Mining Branch, U. S. Bureau of Mines, to accept that of geologist for the Republic Steel Corporation, Cleveland, Ohio.

C. H. BURGESS, geologist, recently joined the staff of the M. A. Hanna Company on the Cayuna range.

WALLACE D. LOWRY, EWART M. BALDWIN and JOHN ELIOT ALLEN have left the Oregon Department of Geology and Mineral Industries. Mr. Lowry has been engaged as geologist with the Texas Company in California, Mr. Baldwin has accepted the position of assistant professor of Geology, University of Oregon at Eugene, and Mr. Allen, department geologist for ten years, has become associate professor of geology at Pennsylvania State College.

PETER MOSIER, who recently received his master's degree in mining from the University of Arizona, is employed by the Phelps Dodge Corporation as a geologist.

JULIAN W. FEISS, Washington, D. C., editor of the *Mining Congress Journal*, has been appointed to the newly established post of assistant to the director of the U. S. Bureau of Mines, and will assume his duties in December.

GEOPHYSICAL ABSTRACTS will again be published by the United States Geological Survey after a 4-year interval during which they were issued by the U. S. Bureau of Mines. The Geophysical Abstracts are published quarterly as an aid to those engaged in geophysical research and exploration. The bulletin covers world literature on geophysics contained in periodicals, books, and patents. It deals with exploration by gravitational, magnetic, seismic, electrical, radioactive, geothermal, and geochemical methods and with underlying geophysical theory and related subjects. Copies may be purchased singly or by annual subscription from the Superintendent of Documents, Government Printing Office, Washington 25, D. C. For subscription, the Superintendent of Documents will accept a deposit of $5.00 in payment for subsequent issues. When this fund is near depletion the subscriber will be notified. The deposit may also be used to cover purchase of any other publication from the Superintendent of Documents.

The Pan American Institute of Mining Engineering and Geology, United States Section, has elected the following new officers: W. D. Johnston, Jr., U. S. Geological Survey, Washington, D. C., Chairman; Francis Cameron and George M. Knebel, Vice Chairmen; Edward J. Craig, Harmon-on-Hudson, New York, Secretary-Treasurer; Francis Cameron, M. L. Jacobs, W. D. Johnston, Jr., George M. Knebel, Thomas H. Miller, Richard S. Newlin, Edward Steidle, Arthur T. Ward, William E. Wrather, and Charles Will Wright, Directors. The next meeting will be in conjunction with the AIME in New York in February, 1948, when a program of papers on Latin America will be presented. The annual luncheon will be held at that time. Plans are being made for the 3rd Congress of Pan American Mining Engineering and Geology to be held in the United States in 1949. The 1st Congress met in Santiago, Chile, in 1942 and the 2nd Congress in Rio de Janeiro, Brazil, in 1946.

JOHN K. GUSTAFSON has been named Director of the Division of Raw Materials established by the U. S. Atomic Energy Commission. This Division is responsible for the Commission's activities with respect to raw materials, including exploration, development, and procurement of raw materials required by the Commission's program. An Advisory Committee for Exploration and Mining was also established with the following members: Donald H. McLaughlin, Chairman; G. Temple Bridgman, Everette L. DeGolyer, Anton Gray, Wilber Judson, Robert E. McConnell and Fred Searls, Jr.

MR. HOMER JENSEN, of Aero Service Corporation, Philadelphia, told the New York Section of the A.I.M.M.E. at their October meeting that their company mapped thousands of square miles with the airborne magnetometer during the past 10 months with results considerably more successful than hoped for and more significant than the history of magnetics had led them to expect. He pointed out its value as a geophysical exploration tool for rapid reconnaissance. But he pointed out that it is not to be considered as a wonder tool.

The American Association of Petroleum Geologists will hold an Eastern Interior regional meeting at St. Louis, Mo., January 14 and 15, 1948, at which there will be presented a group of papers on the stratigraphy and geology of the Eastern Interior Basin, and adjacent areas, and the geology of typical oil fields in the region.

The West Virginia Geological Survey celebrated its Fiftieth Anniversay on December 5, 1947, by a joint meeting with the Appalachian Geological Society of Charleston, and the Oil and Gas Section of the Engineers Society of Western Pennsylvania, Pittsburgh.

## EMMONS MEMORIAL FELLOWSHIP

The S. F. Emmons Memorial Fellowship in Economic Geology is available for the academic year 1948–1949, with a stipend of $1,500.00. Applications and accompanying testimonials should be submitted not later than March 1, 1948. Applicants should be qualified by training and experience to investigate some problems in Economic Geology and should submit a definite statement of the problem to the Committee, under whose oversight the work may be undertaken at any institution approved by them. The Fellow must give entire time to the problem, which may be used for a doctorate dissertation. Application blanks may be obtained from Alan M. Bateman, Yale University, L. C. Graton, Harvard University, Paul F. Kerr, Columbia University, or the Secretary, Columbia University.

The Fellowship will be awarded again for the academic year 1949–50, announcement of which will be made late in 1948.

# INDEX TO VOLUME XLII

[NOTE.—In this index the titles of principal papers and headings of departments, as *Discussions*, are in italics.]


Abrasives, Texas (review), 501
*Abstracts*—
Applications of the concept of zonal structure in pegmatites to prospecting for feldspar (Cameron), 420
Applied geology at the Magma mine, Superior, Arizona (Michell), 416
Bedding replacement fluorspar deposits of Spar Valley, Eagle Mountains, Texas (Gillerman), 416
Beryl resources of Connecticut (Cameron and Shainin), 353
Coal in Japan colliery operations and methods of mining (Cammack), 422
Cobalt mineralization in the Blackbird district, Lemhi County, Idaho (Anderson), 22
Eastern part (Malartic to Pershing) of the Kirkland-Val d'Or break (Norman), 412
Eolian dam near Tucumcari, New Mexico (Dobrovolny and Townsend), 492
Factors in the deposition of hydrothermal ores (Hulin), 413
Genesis of intrusive magnetite and related ores (Shand), 634
Geology and ground-water resources of Puerto Rico (McGuinness), 409, 563
Geology of the Batuco lead-zinc deposits in central Chile (McAllister and Shainin), 417
Geology of the Colquiri tin mine, Bolivia (Campbell), 1
Geology of the Red Rose tungsten mine, Hazelton, British Columbia (Stevenson), 434
Graphite deposits of southern Korea (Overstreet), 424
Ground-water conditions and problems in the upper Mississippi River embayment (Schneider), 626
Ground-water investigations in the Iron River mining district, Michigan (Theis and Stuart), 410
Hydroelectric power development in Japan (Bell and Williams), 424
Hydrothermal alteration in the "Porphyry Copper" deposits (Schwartz), 319
Hydrothermal gypsum in Japan (Jenke), 426
Iron and steel industry of the former Japanese Empire (Johnston), 427
*Abstracts—Continued*
Location of Bull Shoals Dam (Roberts), 410
Low-temperature carbonization of coal in Japan (Reid), 428
Magnesite deposit at Gabbs, Nevada (Vitaliano and Callaghan), 420
Metalliferous geochemical zones of Australia (Hills), 478
Metallurgical interpretation of ore genesis—An alternative to the hydrothermal theory (Brown), 413
Metasomatic processes (Holser), 384
Methods and objectives in engineering geology in the Tennessee Valley Authority (Moneymaker), 411
Mineral investigations in TVA reservoirs (Moneymaker), 411
Mining and geology studies in Japan (Singewald), 421
Ongjin-Haeju deposit, southern Korea (Klepper), 422
Ore deposits and geologic age (Miholić), 713
Ore deposits of the eastern Andes of Bolivia. The Cordillera Real (Turneaure and Welker), 595
Origin of gold placers in northern Tierra del Fuego (Shainin), 418
Original Sixteen to One gold-quartz vein, Alleghany, California (Cooke), 211
Pennsylvanian clay horizons of western Maryland (Waage), 420
Petrographic features of sheet muscovite in southeastern United States as related to commercial classifications (Jahns), 418
Phosphate deposits of the eastern province, Uganda (Davies), 137
Phosphate deposits of the former Japanese islands (Rodgers), 425
Pyrite geo-thermometer (Smith), 515
Regional structural features of the Yellowknife area (Campbell), 687
Research on geochemical prospecting by the Geological Survey (Hawkes), 414
Resumé of the mineral industry in southern Korea (Gallagher), 427
Sangdong tungsten deposit, southern Korea (Klepper), 465
Scheelite in the Boulder district, Colorado (Tweto), 47

*Abstracts—Continued*
Search for concealed deposits—A reorientation of philosophy (Lasky), 415
Search for ore deposits—Geologic methods and concepts (Chace), 414
Shallow, high-temperature pegmatites, Grant County, New Mexico (Kelley and Branson), 699
Some physical characteristics of certain favorable and unfavorable ore horizons (Rove), 57, 161
Some pipe deposits of eastern Australia (Blanchard), 265
Some solutional features of the limestone near Lexington, Kentucky (Hamilton), 409
Structural control and wallrock alteration at the Wilbert mine, Dome district, Butte County, Idaho (Anderson), 368, 415
Structural control of fluorspar deposits in the Zuni Mountains, New Mexico (Goddard), 417
Structural principles controlling the occurrence of ore in the Kolar gold field (Bichan), 93
Structure and ore deposits of the Kirkland Lake, Noranda, Val d'Or belt, Ontario and Quebec, 428; (Wilson), 412
(western or Ontario section) (Thomson), 412
Studies of mineral sulpho-salts: XI—Wittichenite (klaprothite) (Nuffield), 147
Sulphur deposits of Japan (Chidester), 425
Talc deposits of the Gouverneur district, New York (Engel), 419
Temperature of crystallization of a fluorite crystal from Luna County, New Mexico (Twenhofel), 78
Tin-tungsten deposit in Egypt (Amin), 637
Transport and deposition of the nonsulphide vein materials. II. Cassiterite (Smith), 251
Tungsten in Japan and Korea (Klepper), 421
Ubiquity of gold values and their relation to zones of tensional dilation (Bichan), 396
Yang-chia-chang-tzu molybdenite district, Manchuria (Hendricks), 426
Zinc content of plants on the Friedensville zinc slime ponds in relation to biogeochemical prospecting (Robinson, Lakin, and Reichen), 572
Zoned magnetite-bearing pegmatites in central Chile (Shainin), 417
Adair, G. S., on membrane equilibrium (review), 749
*Age, Ore deposits and geologic* (Miholić), 713
Aggregates, research, 741
Ahlfeld, F., on geology, Bolivia, 1
on the Cordillera Real, Bolivia, 598
on tin, 251
on veins, 609
on wittichenite, 156
on wolframite, 289
on zoning, 666
review of book by, 86
Ahlfeld, F., and Muñoz Reyes, J., on Permian, Bolivia, 598
Alabama, ground water, Mississippi River embayment, 626
petroleum, report (review), 86
Albite, 117, 323
Alexander, A. E., on colloids (review), 749
Alexander, J., on diffusion, 389
Allen, E. T., and Zies, E. G., on hydrogen sulphide, 19
Alling, H. L., on pegmatites, 708
Alteration, Ajo district, Ariz. (review), 585
Igla district, Egypt, 656
Kirkland Lake-Val d'Or belt, Ont.-Que. (abstract), 429
Kolar gold field, 121
Red Rose tungsten mine, B. C., 451
research, 528
scheelite veins, Boulder, Colo., 48
Sixteen to One vein, Calif., 211, 219
titanium deposits, Va., 196
Wilbert mine, Idaho, 376
Yellowknife area, N.W.T., 696
*Alteration as a guide to ore, Sericite-kaolin* (Lovering), 534
*Alteration at the Wilbert mine, Dome district, Butte County, Idaho, Structural control and wall-rock* (Anderson), 368
*Alteration in the "Porphyry Copper" deposits, Hydrothermal* (Schwartz), 319
Alunite, 332, 346
Amin, M. S., *A tin-tungsten deposit in Egypt*, 637–671
on Igla area, Egypt, 639
Anderson, A. L., *Cobalt mineralization in the Blackbird district, Lemhi County, Idaho*, 22–46
*Structural control and wall-rock alteration at the Wilbert mine, Dome district, Butte County, Idaho*, 368–383
abstract by, 415
communication by, 305
on cobalt, 23
on gabbro, 25
on Idaho batholith, 25
on pegmatites, 709
Anderson, A. L., and Wagner, W. R., on faults, 371
*Andes of Bolivia. The Cordillera Real. The ore deposits of the eastern* (Turneaure and Welker), 595
Andrews, E. C., on quartz, 269
Antilles, Greater, structure, 563

Antimony, Cordillera Real, Bolivia, 610, 618
sulfosalts, Clark Fork, Idaho, 305
Apatite, 139, 197, 447, 471
Aramayo, C. V., review of pamphlet by, 748
Argentina, geological work by B. Willis (review), 501
Arizona, Bisbee district, mineralization, 69
copper, Ajo district (review), 583
alteration about porphyry deposits, 323, 339
Magma mine (abstract), 416
Arkansas, Bull Shoals Dam (abstract), 410
ground water, Mississippi River embayment, 626
petroleum, report (review), 86
Arsenopyrite, 33, 38, 234, 450
Association index, 242
Atom shunting, 394
*Australia, Some pipe deposits of eastern* (Blanchard), 265
*The metalliferous geochemical zones of* (Hills), 478
Australian Shield, 482

Backlund, H. G., on igneous rocks, 138
Bacteria, study of sediment formation, 677
Bain, G. W., on absorption, 61
on precipitation and solution, 389
Ball, L. C., on molybdenite, 273
Barclay, R. E., review of book by, 87
Barite, Texas (review), 501
Barnes, V. E., industrial minerals, Texas (review), 501
Barnes, V. E., Cloud, P. E., Jr., and Warren, L. E., Devonian, Texas (review), 501
Barrer, R. M., on diffusion, 390
Barton, W. H., Jr., and Doane, L. H., on toughness tests, 180
Bastin, E. S., on lead and zinc, 525
on metal deposits, 529
on pegmatites, 709, 711
Bastin, E. S., *et al.*, on ore minerals, 525
Bateman, A. M., on alteration, 320
on Ely district, Nev., 336
on mineral deposits, 725
on mineralization, 646
on openings, 384
on ore fluid, 290
Batholiths, Cordillera Real, Bolivia, 600
Bayley, W. S., on iron, 634
Beath, O. A., on selenium, 574
Beaumont, E. de, on magmas, 708
Becker, G. F., on rupture, 174
Beers, R. F., *Expansion of geophysical methods applicable to ore*, 545–547
Beeson, J. J., on alteration, 325
Behre, C. H., Jr., *Geochemistry and localization of dolomitization*, 540–542
on Alma district, Colo., 68
*Behre, C. H., Jr.—Continued*
on research, 737
report by, 505
Belgian Congo, 404
Bell, F. M., and Williams, M. R., abstract by, 424
Bellows, G., on slate, 603
Bennett, H. H., review of book by, 307
Bentonite, research, 741
Berl, E., and von Taack, F., on iron, 636
Berry, E. W., on Pliocene plants, 602
on volcanism, Bolivia, 5
*Beryl resources of Connecticut* (Cameron and Shainin), 353
Beyschlag, F., Krusch, P., and Vogt, J. H. L., on carbonates, 541
Bibliography, Australia, metallogenetic zones, 490
cassiterite, transport and deposition, 263
ground water, Mississippi River embayment, 632
Igla district, Egypt, 670
Kolar gold field, 135
mineral deposits and magmas, 736
ore horizons, physical properties, 192
ore localization, 536
ore transport and volcanism, 538
petroleum (review), 588
pipe deposits, Australia, 303
pyrite geothermometer, 523
Sangdong tungsten mine, Korea, 476
silica, transport and deposition, 562
wittichenite, 159
zinc content of soils and vegetation, 581
Bichan, W. J., *Structural principles controlling the occurrence of ore in the Kolar gold field*, 93–136
*The ubiquity of gold values and their relation to zones of tensional dilation*, 396–403
on metals, 132
on solutions, 120
Billingsley, P., and Locke, A., on structure, 58
*Biogeochemical prospecting, The zinc content of plants on the Friedensville zinc slime ponds in relation to* (Robinson, Lakin, and Reichen), 572
Biotite, 9, 27, 324, 334, 337, 347, 447, 471, 706
Birch, A. F., Schairer, J. F., and Spicer, H. C., on physical constants, 530
Bismuth, Cordillera Real, Boliva, 610
pipe deposits, Australia, 265
Bismuthinite, 610
*Blackbird district, Lemhi County, Idaho, Cobalt mineralization in the* (Anderson), 22
Blanchard, R., *Detailed studies of zoning in ore districts*, 543–545
*Some pipe deposits of eastern Australia*, 265–304
Blanckenhorn, M., on carbonatization, 541

*Bolivia, Geology of the Colquiri tin mine,* (Campbell), 1
*The Cordillera Real. The ore deposits of the eastern Andes of* (Turneaure and Welker), 595
geology (review), 86
mining (review), 748
zoning, Chicote area, 289
Bonillas, Y. S., Tenney, J. B., and Feuchere, L., on Bisbee area, Ariz., 69
*Books received,* 88, 200, 308, 406, 501, 589, 680, 749
Boron, geochemistry, 729
Bottoming indices, 551
*Boulder district, Colorado, Scheelite in the* (Tweto), 47
Boutwell, J. M., on alteration, 325
Bowen, N. L., on vein minerals, 220
Bowley, H., on ore deposits, 482
Boydell, H. C., on fluid flow, 386
on mineral deposition, 387
Brajnikov, B., on silicates, 722
Branson, O. T., with Kelley, V. C., *Shallow, high-temperature pegmatites, Grant County, New Mexico,* 699–712
Bray, J. M., on minerals, 460
Brazil, platinum, Morro do Pilar deposit, 735
Brenchley, W. E., on zinc, 573
*British Columbia, Geology of the Red Rose tungsten mine, Hazelton* (Stevenson), 433
Broderick, A. T., books received, 88, 200, 308, 406, 501, 680, 749
Brögger, W. C., on igneous rocks, 138
Brown, J. C., on quartz, 286
on tungsten, 288
Brown, J. C., and Heron, A. M., on cassiterite, 288
on wolframite, 288
Brown, J. S., *Causes for the selective localization of ore in certain limestone beds,* 535–536
abstract by, 413
Brown, W. H., on Austinville area, Va., 74
Brüggen, J., on tuffs, Bolivia, 602
Bryan, W. H., and Jones, O. A., on folding, 482
Bucher, W. H., on rupture, 168
Buddington, A. F., *Comparison between "productive" and "barren" igneous rocks,* 539–540
on granodiorite, 440
on molybdenite, 287
on xenothermal ore deposits, 620, 640, 712
Buerger, M. J., on subcapillary openings, 389
Buerger, M. J., and Maury, J. L., on tin, 251
Building stones, research, 742
Bunn, C. W., on crystals, 551
Burma, zoning, Tavoy district, 288
Butler, B. S., *et al.,* on alteration, 325
on molybdenite, 287
on specularite, 521
review by, 583
Butler, B. S., and Wilson, E. D., on sulphides, 324
Byers, H. G., *et al.,* on selenium, 574

Cady, G. H., report by, 509
Calcite, 345, 645
*California, The original Sixteen to One gold-quartz vein, Alleghany* (Cooke), 211
Calkins, F. C., memorial by, 313
Cameron, E. N., abstract by, 420
Cameron, E. N., and Shainin, V. E., *The beryl resources of Connecticut,* 353–367
Cameron, E. N., *et al.,* on pegmatites, 354, 709
Cammack, K. V., abstract by, 422
Campbell, D. F., *Geology of the Colquiri tin mine, Bolivia,* 1–21
Campbell, J. M., on tin, 288
on wolframite, 288
Campbell, N., *Regional structural features of the Yellowknife area,* 687–698
Canada, coal reserves (review), 679
Yellowknife area, structure, 687
Capillary openings, 385
Carbonate, 217, 233
Carbonatite, 141
Carbonatization, 377, 540
Carlé, W., on faults, 718
Cassiterite, 1, 9, 609, 648
*Transport and deposition of the non-sulphide vein materials* (Smith), 251
pipe deposits, Australia, 265
Cave, G. C. B., analyses by, 440, 452
Cederstrom, D. J., review by, 498
Celestite, Texas (review), 501
Chace, F. M., abstract by, 414
Chalcedony, 378
Chalcocite, 394, 586
Chalcopyrite, 35, 38, 238, 294, 450
Charpentier, J. von, on pegmatites, 708
Chemical analyses, dike rock, Bukusu Hill, Uganda, 142
gold assays, Kolar field, 129
granodiorites, B. C., 440
mica, Nevada, 337
mineral waters, Yugoslavia, 715
minerals (review), 86
spessartite, 270
zinc in soil and vegetation, 575
Chidester, A. H., abstract by, 425
Chile, Batuco lead-zinc deposits (abstract), 417
gold, placers, Tierra del Fuego (abstract), 418
magnetite pegmatites (abstract), 417
China, iron and steel, North China (abstract), 427
zoning, tungsten deposits, 289

Chlorite, 450
Chrysotile, 217
Church, A. H., on aluminum, 579
Clarke, E. de C., on ore deposits, 487
Clarke, W. B., on gold, 487
Clays, Maryland, Pennsylvanian horizons (abstract), 420
research, 742
study of minerals, 677
Cloos, E., on granodiorite, 250
Cloud, P. E., Jr., Barnes, V. E., and Bridge, J., Ellenburger group, Texas (review), 501
Coal, Canada (review), 679
Japan, low-temperature carbonization (abstract), 428
mining (abstract), 422
Research Committee report, 509
Texas (review), 501
*Cobalt mineralization in the Blackbird district, Lemhi County, Idaho* (Anderson), 22
Coker, R. E., review of book by, 406
Colloids (review), 749
mineralization, 529
Colloids and replacement, 388
Colony, R. J., on magnetite, 634
*Colorado, Scheelite in the Boulder district* (Tweto), 47
Alma district, limestone, permeability tests, 68
Gilman area, mineralization, 72
*Colquiri tin mine, Bolivia, Geology of the* (Campbell), 1
*Committee of the Society of Economic Geologists, Report on ground water by the Research* (Meinzer), 672
*Committee on Basic Research in the Field of Industrial Minerals and Rocks, Report of* (Gillson and Jahns,) 737
*Committee on Research on Ore Deposits of the Society of Economic Geologists, Report of the* (Johnston), 524
*Committee on Research on Petroleum, Society of Economic Geologists, Report of the* (Heald), 676
*Connecticut, The beryl resources of* (Cameron and Shainin), 353
Conolly, H. J. C., on gold, 247
Continents, regions (review), 87
Cooke, H. R., Jr., *The original Sixteen to One gold-quartz vein, Alleghany, California*, 211–250
Coombe, A. D., and Groves, A. W., on tin, 251
Copper, Arizona, Ajo district (review), 583
Magma mine (abstract), 416
Australia, zones, 480
Belgian Congo (review), 404
Blackbird district, Idaho, 22
Bolivia, mining (review), 748
Cordillera Real, Bolivia, 610
geochemistry, 730
*Copper—Continued*
Korea, Ongjin-Haeju deposit (abstract), 422
Noranda-Val d'Or belt Ont.-Que. (abstract), 428
pipe deposits, Australia, 265
plant indicators, 573
Quebec, Kirkland-Val d'Or break (abstract), 412
Tennessee, Ducktown district, history (review), 87
*Copper" deposits, Hydrothermal alteration in the "Porphyry* (Schwartz), 319
Corn, zinc content, Pa., 576
Crawford, J., on dolomite, 541
Crawford, R. D., and Gibson, R., on Gilman area, Colo., 72
Cronshaw, H. B., on wolframite, 288
Crosby, W. O., and Fuller, M. L., on pegmatites, 708
Crossings, 245
Crowley, A. J., Ellenburger limestone, Texas (review), 501
*Crystallization of a fluorite crystal from Luna County, New Mexico, The temperature of* (Twenhofel), 78
Crystallography, wittichenite, 148
Crystals, electrical properties, 515
Currier, L. W., on ore deposition, 192
on structure, 58

Daly, R. A., on water, 254
*Dam near Tucumcari, New Mexico, Aeolian* (Dobrovolny and Townsend), 492
Damon, H. G., spiculite, Lampasas Co., Texas (review), 501
Dams, Bull Shoals Dam, Ark. (abstract), 410
Japan, hydroelectric power (abstract), 424
Tenn. Valley Authority, geologic investigation (abstract), 411
Dana, E. S., and Ford, W. E., on gearksutite, 12
Dana, J. D., and Dana, E. S., on klaprothite, 147
Daubrée, A., on cassiterite, 251
David, T. W. E., on phosphate zone, 479
Davidson, D. M., Grout, F. F., and Schwartz, G. M., discussion of paper by, 194
Davidson, S., on solutions, 402
Davies, K. A., *Phosphate deposits of the eastern province, Uganda*, 137–146
Davis, E. W., on iron ore, 207
Davison, E. H., on zoning, 666
Davtyan, O. K., on diffusion, 388
Davy, W. M., on Cordillera Real, Bolivia, 598
on tin, 251
Davy, W. M., and Farnham, C. M., on wittichenite, 152

*Deposition of silica, Transportation and* (Ingerson), 560
*Deposition of the non-sulphide vein materials. II. Cassiterite, Transport and* (Smith), 251
*Deposits, Hydrothermal alteration in the "Porphyry Copper"* (Schwartz), 319
*Deposits of magmatic origin, Mineral* (Guimarães), 721
Derry, D. R., on tin, 251
Dewey, H., on zoning, 666
Diagrams—
block diagrams, tin pipe, Herberton, Queensland, 284
bomb for cassiterite synthesis, 253
fluorite, temperature zoning, 81
fracture pattern Red Rose mine, B. C., 444
paragenesis, ores, cobalt, Blackbird district, Idaho, 31
gold, Sixteen to One vein, Calif., 232
tin, Colquiri, Bolivia, 9
pegmatite units, Conn., 356
permeability testing apparatus, 63
photomicrographs, scheelite, Boulder, Colo., 49
pyrite geothermometer, 519
structure, Kolar gold field, 111
texture of ores, 218
Diatomite, Texas (review), 501
Dictionaries, chemical and technical (review), 307
Differentiation and mineralization, 540
Diffusion, 387
Dikes, Amherst and Nelson Counties, Va., 194
Bisbee area, Ariz., 344
Bukusu Hill area, Uganda, 141
Colquiri district, Bolivia, 5
Cordillera Real, Bolivia, 601
Herberton-Watsonville, Australia, 294
Igla area, Egypt, 640
Kolar gold field, 98
Miami district, Ariz., 329
Red Rose tungsten mine area, B. C., 440
Western Australia, 482
Wilbert mine, Idaho, 370
Yellowknife area, N.W.T., 690, 694
*Dilation, The ubiquity of gold values and their relation to zones of tensional* (Bichan), 396
*Discussions*—
Lead-silver mineralization in the Clark Fork district (Anderson), Anderson, 305
Virginia titanium deposits (Davidson, Grout, and Schwartz), Ross, 194
Dobrovolny, E., and Summerson, C. H., on Tucumcari district, N. Mex., 492
Dobrovolny, E., and Townsend, R. C., *An eolian dam near Tucumcari, New Mexico*, 492–497
Dogger, Kolar gold field, 96, 101
Dognacskite, 159
Dolar-Mantuani, L., on tonalite, 715
*Dolomitization, Geochemistry and localization of* (Behre), 540
*Dome district, Butte County, Idaho, Structural control and wall-rock alteration at the Wilbert mine* (Anderson), 368
Dorn, V. P., on zinc, 573
Dougherty, E. Y., on alteration, 121
Douglas, G. V., on ore deposition, 394
Douglas, G. V., Goodman, N. R., and Milligan, G. C., on replacement, 393
Douglas, L. B. E., on shears, 220
Drugman, J., on fluorite, 81
Duffell, S., on flow of solutions, 386
Dunn, J. A., on metamorphism, 480
on wolframite, 289
Duricrust, Uganda, 138
du Toit, A. L., on Gondwanaland, 490

Earthquakes (review), 680
*Editorials*—
Petroleum on the continental shelves (Pratt), 83
*Egypt, A tin-tungsten deposit in* (Amin), 637
Eirich, F., on macromolecules (review), 749
Eitel, W., on carbonates, 540
Electrum, 36
Eley, D. D., on colloids (review), 749
*Emanations as keys to ore transport, Volcanic* (Ross), 537
Emmons, S. F., Irving, J. D., and Loughlin, G. F., on carbonates, 540
Emmons, W. H., on alteration, 320
on ore horizons, 178
on zoning, 288
Emplectite, 150
Enargite, 39
Engel, A. E. J., abstract by, 419
Engineering geology (review), 406
Tennessee Valley Authority (abstract), 411
England, zoning, Cornwall, 287
Engler, K., Thompson, D. G., and Kazmann, R. G., on water, 626
Enrichment, copper, Ajo district, Ariz. (review), 586
*Eolian dam near Tucumcari, New Mexico* (Dobrovolny and Townsend), 492
Epidote, 345, 378
Ermakov, N. P., on crystallization, 78
Erosion, soil conservation (review), 307
Eskola, P., on subcapillary openings, 389
Evans, G. L., industrial minerals, Texas (review), 501
Ewald, P. P., and Renninger, M., on "mosaic blocks," 388
Experiments, cassiterite transport and deposition, 254
ore horizon properties, 59
pyrite geothermometer, 518
quartz crystal synthesis, 561

Fairbairn, H. W., on minerals, 460
Fairbanks, E. E., on minerals, 305
Fairchild, J. G., analysis by, 440
Fancher, G. H., Lewis, J. A., and Barnes, K. B., on permeability, 62
Farmin, R., on gold, 240
Faults, Ajo district, Ariz. (review), 584
Alpine zone, Yugoslavia, 714
Antilles, Greater, 564
Basin-and-Range Province, 557
Blackbird district, Idaho, 26
Colquiri district, Bolivia, 6
Cordillera Real, Bolivia, 604
fluorspar deposits, Zuni Mtns., N. Mex. (abstract), 417
Hawaii (review), 498
Kirkland Lake-Val d'Or belt, Ont.-Que (abstract), 429
Kolar gold field, 102
Ontario-Quebec, Kirkland Lake-Val d'Or break (abstract), 412
Red Rose tungsten mine, B. C., 452
research, 678
Sangdong area, Korea, 470
Sixteen to One vein, Calif., 213, 219, 228
Texas, Houston Co. (review), 501
Wilbert mine, Idaho, 370
Yellowknife area, N.W.T., 687
Feldspar, 646
pegmatite prospecting (abstract), 420
Texas (review), 501
Feldspathization, 376
Fences about minerals, 233
Fenner, C. N., on cassiterite, 302
on magma, 635
Ferberite, 47, 445
Ferguson, H. C., and Gannett, R. W., on gold, 212
Fersmann, A., on pegmatite, 732
Fick's equation, 387
Fluorite, 10, 645, 654
New Mexico, Zuni Mtns. (abstract), 417
Texas (review), 501
Spar Valley (abstract), 416
*Fluorite crystal from Luna County, New Mexico, The temperature of crystallization of a* (Twenhofel), 78
Folds, Colquiri district, Peru, 5
Cordillera Real, Bolivia, 604
Kolar gold field, 94
Wilbert mine, Idaho, 370
Yellowknife Bay, N.W.T., 692
Forster, R., on tin, 252
Fowler, G. M., on ore horizons, 74
Fowler, G. M., and Lyden, J. P., on limestone, 67
on Tri-State district, 74
Fractures, Cordillera Real, Bolivia, 608
rocks, 169
France, mineral waters, analyses, 717
Francolite, 143
Frenkel, J., on interstitial ions, 391
Fresenius, R., and Fresenius, H., chemical analyses by, 716
Fresenius, R., and Hintz, E., analysis by, 716
*Friedensville zinc slime ponds in relation to biogeochemical prospecting, The zinc content of plants on the* (Robinson, Lakin, and Reichen), 572
Fries, C., Jr., and Schmitter, E., on tactite, 474
Frondel, C., on replacement, 388
Fuchs, W. M., review of book by, 748

Gabbros, magnetite genesis, 635
Galena, 11, 39, 52, 371, 417, 523
Gallagher, D., abstract by, 427
Garnet, pipe deposits, Australia, 269
Garrels, R. M., on metal ions, 542
on replacement, 388
Gaudin, A. M., and Dicke, G., on emplectite, 149
Gay, R., on diffusion, 387
Gearksutite, 10
Geijer, P., on magnetite, 634
Genesis, hydrothermal ores, 413
metallurgical interpretation (abstract), 413
*Genesis of intrusive magnetite and related ores* (Shand), 634
Geochemical prospecting (abstract), 414
*Geochemical zones of Australia, The metalliferous* (Hills), 478
Geochemistry, ground water, 675
migration of elements, 729
mineralization and igneous rocks, 540
petroleum (review), 588
zinc, Friedensville slime ponds, 572
*Geochemistry and localization of dolomitization* (Behre), 540
Geography, regions of the world (review), 87
*Geologic age, Ore deposits and* (Miholić), 713
Geological maps, Bukusu Hill, Uganda, 140
Gotta-Walden beryl deposit, Conn., 363
Igla tin-tungsten mine district, Egypt, 639
Kolar gold field, 99
Mississippi River embayment, 627
ore deposits, Cordillera Real, Bolivia, 597
pipe deposits, Australia, 271
Red Rose tungsten mine area, British Columbia, 438
Sangdong tungsten area, Korea, 469
Sixteen to One vein, Calif., 213
Tucumcari district, N. Mexico, 493
Yellowknife Bay, N.W.T., 689
Geology, 405
Batuco lead-zinc deposits, Chile (abstract), 417
Belgian Congo (review), 404
Bolivia (review), 86
Cordillera Real, Bolivia, 598
Igla area, Egypt, 639
Kolar gold field, 95

*Geology—Continued*
Mesabi Range, Minn. (review), 199
Mississippi River embayment, 629
pegmatites, Grant Co., N. M., 701
Puerto Rico (abstract), 409
Sangdong tungsten deposit, Korea, 468
Sixteen to One vein, Calif., 212
tungsten (review), 500
Venezuela and Trinidad (review), 588
Yellowknife Bay area, N.W.T., 688
*Geology and ground-water resources of Puerto Rico* (McGuinness), 563
*Geology of the Colquiri tin mine, Bolivia* (Campbell), 1
*Geology of the Red Rose tungsten mine, Hazelton, British Columbia* (Stevenson), 433
Geomorphology (review), 307
*Geophysical methods applicable to ore, Expansion of* (Beers), 545
Geophysical prospecting, ground water, 674
petroleum (review), 588
Geosynclines and metallogenesis, 732
Geothermal gradient, 719
*Geo-thermometer, The pyrite* (Smith), 515
Germany, mineral waters, analyses, 716
wittichenite, Schapbachthal, Baden, 147
Gevers, T. W., and Frommurze, H. F., on tin, 251
Gibson, R. E., on quartz, 117, 220
on solutions, 551
Gillerman, E., abstract by, 416
Gillson, J. L., and Jahns, R. H., *Report of Committee on Basic Research in the Field of Industrial Minerals and Rocks*, 737–746
Gilluly, J., on alteration, 320, 323
on copper, 351
review of monograph by, 583
Goddard, E. N., abstract by, 417
Gold, Ajo district, Ariz. (review), 583
Australia, zones, 484
Blackbird district, Idaho, 22, 40
Chile, placers of Tierra del Fuego (abstract), 418
Cordillera Real, Bolivia, 609
Kirkland Lake Val d'Or belt, Ont.-Que. (abstract), 428
Korea, Ongjin-Haeju deposit (abstract), 422
pipe deposits, Australia, 275
Quebec, Kirkland-Val d'Or break (abstract), 412
Wilbert mine, Idaho, 371
*Gold field, Structural principles controlling the occurrence of ore in the Kolar* (Bichan), 93
*Gold values and their relation to zones of tensional dilation, The ubiquity of* (Bichan), 396
*Gold-quartz vein, Alleghany, California, The original Sixteen to One* (Cooke), 211
Goldschmidt, V. M., on chemical elements, 730
on minerals, 455
on silicates, 721
Gonyer, F. A., analysis by, 440
Goranson, R. W., on water, 254, 522, 707
Gorjanović, D., on faults, 714
Gouge, 233
scheelite replacement, Boulder, Colo., 51
Grain boundaries and openings, 390
Graphite, Korea (abstract), 424
Graphs, gold, correlation of vein dip and thickness, 249
viscous flow, 65
Graton, L. C., *Causes for downward limits of hypogene deposits*, 547–556
on ore deposition, 621
on ore solutions, 220, 640
on quartz, 221
on telescoping, 300
on telethermal zone, 383
*Great Basin, Accurate mapping* (Lasky), 556
Gregory, H. E., and Robinson, H. H., on pegmatites, 354
Greisen, 269, 649
Griffitts, W. R., *et al.*, on pegmatites, 709
Griggs, D. T., on elastic limit, 161
Griggs wedge effect, 166
Gross, J., on limestones, 182
*Ground water by the Research Committee of the Society of Economic Geologists, Report on* (Meinzer), 672
*Ground-water conditions and problems in the upper Mississippi River embayment* (Schneider), 626
*Ground-water resources of Puerto Rico, Geology and* (McGuinness), 563
Grout, F. F., on pegmatites, 710
Gruner, J. W., review of book by, 199
Guimarães, D., *Mineral deposits of magmatic origin*, 721–736
on magma, 726
on solid solution, 721
Gypsum, Japan, hydrothermal deposits (abstract), 426
Texas, Edwards limestone (review), 501

Haag, H. L., on cassiterite, 288
Hamberg, N. P., analyses by, 716
Hamilton, D. K., abstract by, 409
Harcourt, G. A., on wittichenite, 152
Harker, A., on pegmatites, 709
Harley, G. T., on Black Range, N. M., 701
Hart, L. H., on zoning, 288
Hatch, F. H., on folds, 112
Hawaii, ground water (review), 498
Kilauea crater (review), 747
Hawkes, H. E., Jr., abstract by, 414
Hayward, M. W., and Triplett, W. H., on dolomite, 541
on ore deposition, 192

Heald, K. C., *Report of the Committee on Research on Petroleum, Society of Economic Geologists*, 676–678
Hedvall, I. A., on solid phase reactions, 392
Heinrich, E. W., on pegmatites, 710
Hendricks, T. A., abstract by, 426
Herdsman, W. H., analysis by, 142
Heritsch, F., on faults, 714
Hess, F. L., on cobalt, 22
on pegmatites, 709
on tactite, 474
on tungsten, 615
Hess, F. L., and Larsen, E. S., on tungsten, 474
Hess, F. L., and Schaller, W. T., on wolframite, 47
Hess, H. H., on carbonatization, 223
Hewett, D. F., on carbonates, 541
on ore deposition, 192
Hewitt, W. P., on pipes, 298
Hietanen, A., on quartz, 230
Hilgard, E. W., on soils, 573
Hilger,—., on copper, 154
Hill, J. M., on cassiterite, 300
Hillebrand, W. F., analysis by, 440
Hills, E. S., *The metalliferous geochemical zones of Australia*, 478–491
on Australian Shield, 480
Hindustan, gold, Kolar field, 93
Hintz, E., analyses by, 716
Hintz, E., and Grünhut, L., analyses by, 716
Hintze, C., on copper, 154
History, Colquiri mining district, Bolivia, 2
Ducktown district, Tennessee (review), 87
Hitchen, C. S., and van Aubel, R., on uraninite, 719
Hoar, T. P., and Price, L. E., on diffusion, 395
Hobbs, S. W., on tactite, 474
Hobbs, S. W., and Clabaugh, S. E., on tungsten ore rock, 474
Hobson, G. V., on ore fluid, 289
Hoeman, E. C., and Redfield, R. C., sand, Rockdale formation, Texas (review), 501
Holden, E. F., on crystallization, 78
Holland, T. H., on quartz, 114
Holmes, A., on specific gravity, 60
on volcanics, 146
Holmes, R. S., on copper, 573
on zinc, 576
Holser, W. T., *Metasomatic processes*, 384–395
Hooke's Law, 172
*Horizons, Some physical characteristics of certain favorable and unfavorable* (Rove), 57, 161
Hornblende, 449
Horsetail, zinc content, Pa., 577
Hot springs and mineralization, 537
Hotchkiss, W. O., *Iron ore supply for the future*, 205–210
Hsu, K. C., on cassiterite, 666
on wolframite, 289
Hubbert, M. K., on models, 530
Hulin, C. D., *Emplacement of igneous rocks in relation to favorable structures*, 558–559
abstract by, 413
on ore structure, 559
Hume, W. F., on Igla area, Egypt, 639
Hunt, T. S., on pegmatites, 708
Hurlbut, E. M., Jr., limestone, Damon Mound, Texas (review), 501
Hussak, E., on platinum, 736
Hydrocarbons, research, 677
*Hydrothermal alteration in the "Porphyry copper" deposits* (Schwartz), 319
*Hypogene deposits, Causes for downward limits of* (Graton), 547

*Idaho, Cobalt mineralization in the Blackbird district, Lemhi County* (Anderson), 22
*Structural control and wall-rock alteration at the Wilbert mine, Dome district, Butte County* (Anderson), 368
Clark Fork district, lead sulfosalts, 305
*Igneous rocks, Comparison between "productive" and "barren"* (Buddington), 539
Black Range, N. M., 701
Red Rose tungsten mine area, B. C., 437
*Igneous rocks in relation to favorable structures, Emplacement of* (Hulin), 558
Illinois, ground water, Mississippi River embayment, 626
Ilmenite, 194
Inclusions, formation of liquid inclusions, 522
quartz, 226
temperature of formation, 78
Indices of bottoming of ores, 551
*Industrial Minerals and Rocks, Report of Committee on Basic Research in the Field of* (Gillson and Jahns), 737
Ingalls, W. R., on cassiterite, 300
Ingerson, E., *Transportation and deposition of silica*, 560–562
*Intrusive magnetite and related ores, The genesis of* (Shand), 634
Iron, Michigan, Iron River district, ground water (abstract), 410
Minnesota, Mesabi Range (review), 199
Iron and steel, Japanese Empire (abstract), 427
*Iron ore supply for the future* (Hotchkiss), 205
Irving, J. D., on openings, 393

Jaggar, T. A., review of book by, 747
Jahns, R. H., abstract by, 418
on pegmatites, 709

Jahns, R. H., with Gillson, J. L., *Report of Committee on Basic Research in the Field of Industrial Minerals and Rocks*, 737–746
Jahns, R. J., on tactite, 474
Japan, coal, low-temperature carbonization (abstract), 428
mining (abstract), 422
gypsum, hydrothermal deposits (abstract), 426
hydroelectric power (abstract), 424
iron and steel (abstract), 427
mining and geology studies (abstract), 421
phosphates, mandated islands (abstract), 425
sulphur deposits (abstract), 425
tungsten (abstract), 421
Jardine, F. M., on beryl, 365
Jenke, A. L., abstract by, 426
Jervis, J., on gold, 487
Johannsen, A., on granodiorite, 441
Johnson, P., on macromolecules (review), 749
Johnston, T. Z., abstract by, 427
Johnston, W. D., Jr., *Report of the Committee on Research on Ore Deposits of the Society of Economic Geologists*, 524–534
on intrusion and mineralization, 558
on pegmatites, 709
Johnston, W. D., Jr., and de Vasconcellos, F. M., on tactite, 474
Joints, Igla district, Egypt, 645
Joliffe, A. W., on faults, 695
on gold, 696
Joly, J., on orogenic movements, 719
Jones, P. J., review of book by, 679
Jones, R. H. B., review by, 199
Jones, W. R., on quartz, 286
Joralemon, I. B., on bottoming of ores, 553
Jordanite, 305
Jost, W., on solid phase reactions, 392

Kansas, Tri-State area, ore horizons, 74
*Kaolin alteration as a guide to ore, Sericite* (Lovering), 534
Kaolinite, 332
Keiser, H. D., review of book edited by, 588
Keller,—, analysis by, 717
Kelley, V. C., and Branson, O. T., *Shallow, high-temperature pegmatites, Grant County, New Mexico*, 699–712
Kelvin, L., and Tait, P. G., on geothermal gradient, 719
Kemp, J. F., on magnetite, 634
on pegmatites, 709
Kennedy, G., on silica, 560
Kennedy, W. Q., on sulphite radical, 143
Kentucky, ground water, Mississippi River embayment, 626
*Kentucky—Continued*
limestone, solution effects (abstract), 409
Kerr, P. F., on granodiorite, 440
on tungsten, 474
Kerr, P. F., and Armstrong, E., on quartz, 560
Ketchum, P. W., Westman, A. E. R., and Hursh, R. K., on permeability, 62
Kieslinger, A., on faults, 714
Kilauea Crater, Hawaii (review), 747
Kindle, E. D., on Hazelton area, B. C., 434
King, B. C., on Mt. Napak, Uganda, 137
Kittl, E., on Cordillera Real, Bolivia, 598
on sediments, 598
(*Klaprothite*), *Studies of mineral sulphosalts: XI—Wittichenite* (Nuffield), 147
Klepper, M. R., *The Sangdong tungsten deposit, southern Korea*, 465–477
abstracts by, 421, 422
Knopf, A., on cassiterite, 300
Knudsen, M., on molecular streaming, 386
Koeberlin, F. R., on tin, 251
*Kolar gold field, Structural principles controlling the occurrence of ore in the* (Bichan), 93
*Korea, The Sangdong tungsten deposit, southern* (Klepper), 465
graphite (abstract), 424
iron and steel (abstract), 427
mineral industry (abstract), 427
Ongjin-Haeju polymetallic deposit (abstract), 422
tungsten (abstract), 421
Korzhinsky, D. S., on diffusion, 387
Kossmat, F., on faults, 717
Kozlowski, R., on Carboniferous, Bolivia, 598
on Cordillera Real, Bolivia, 598
on Devonian of Bolivia, 598
Krieger, P., on klaprothite, 157
Krul, W. F. J. M., and Liefrinck, F. A., review of monograph by, 680
Kuhn, T. H., on feldspar, 585
on molybdenite, 287

Lackey, E. F., and Anderson, E. S., review of book by, 87
Laemmlein, G., on inclusions, 79
Lakin, H. W., Reichen, L. E., with Robinson, W. O., *The zinc content of plants on the Friedensville zinc slime ponds in relation to biogeochemical prospecting*, 572–582
Landes, K. K., on pegmatites, 708, 712
Laney, F. B., on klaprothite, 156
Larsen, E. S., on intrusion and mineralization, 558
Lasky, S. G., *Accurate mapping, Great Basin*, 556–557
abstract by, 415
on Basin-and-Range Province, 556

Lead, Chile, Batuco deposit (abstract), 417
Colorado, Alma district, mineralization, 68
Cordillera Real, Bolivia, 610
geochemistry, 731
Korea, Ongjin-Haeju deposit (abstract), 422
pipe deposits, Australia, 265
sulfosalts, Clark Fork, Idaho, 305
Texas, Mica and Bird mine (review), 501
Wilbert mine, Idaho, 368
Leith, C. K., on wood, 168
Lemke, E., on faults, 718
Lemmon, D. M., on tactite, 474
Leptothermal deposits, 622
Li, K.-C., and Wang, C. Y., on wolframite, 289
review of book by, 500
Liddle, R. A., review of book by, 588
Liesegang, R. E., on diffusion, 387
on openings, 393
Lignite, Canada (review), 679
Limestone, permeability tests, 66
solutional effects, Ky. (abstract), 409
*Limestone beds, Causes for the selective localization of ore in certain* (Brown), 535
Lincoln, F. C., on veins, 609
Lindgren, W., on alteration, 320
on cassiterite, 288
on granodiorite, 440
on hypothermal deposits, 622
on ions, 387
on monzonite, 600
on ore horizons, 178
on porphyry, 342
on pyrometasomatic deposits, 474
on pyroxene, 122
on replacement, 388
on solutions, 454
on tin, 251
on wittichenite, 152
Lindgren, W., and Abbott, A. C., on sediments, 5
on tin, 251
Lindgren, W., and Creveling, J. G., on tin, 251
Lithium, geochemistry, 730
Little, O. H., and Attia, M. I., on tin, 640
Llewellyn, B., on tin ore, 295
Locke, A., on openings, 393
Logging, research, 678
Loughlin, G. F., 1880–1946, a memorial, 313
Loughlin, G. F., and Behre, C. H., Jr., on carbonates, 542
on mesothermal deposits, 622
Louisiana, petroleum, report (review), 86
Lovering, T. S., *Sericite-kaolin alteration as a guide to ore*, 534–535
on alteration, 321, 454
on Boulder district, Colo., 48
on ore deposition, 530
*Lovering, T. S.—Continued*
on scheelite, 48
on shear component, 168

MacAlister, D. A., on wolframite, 287
McAllister, J. F., and Shainin, V. E., abstract by, 417
Macelwane, J. B., review of book by, 680
McGuiness, C. L., *Geology and ground water resources of Puerto Rico*, 563–571
abstract by, 409
McHargue, J. S., and Roy, W. R., on copper and zinc, 573
Mackay, B. R., review of book by, 679
McKee, E. D., on Paleozoic, Ariz., 583
McKinstry, H. E., on flow barriers, 552
on stress diagram, 453
on veins, 608
McKnight, E. T., *et al.*, on dolomite, 542
Maclaren, M., on cassiterite, 288
Magmas, emanations, 724
magnetite, genesis, 634
ore genesis (abstract), 413
trace elements, 527
*Magmatic origin, Mineral deposits of* (Guimarães), 721
Magnesite, Nevada, Gabbs deposit (abstract), 420
Magnetite, 10, 97, 139
Chile, pegmatite deposits (abstract), 417
*Magnetite and related ores, The genesis of intrusive* (Shand), 634
Majer, V., analysis by, 715
Manchuria, iron and steel (abstract), 427
molybdenite, Yang-chia-chang-tzu district (abstract), 426
Manganese, Texas, Potter and Moore Cos. (review), 501
*Mapping, Great Basin, Accurate* (Lasky), 556
Maps, Australia, metallogenetic periods, 481
pipe deposits, 266
Basin-and-Range Province, 557
Blackbird district, Idaho, 23
Colquiri district, Bolivia, 2
copper porphyry deposits, western U. S., 327
Igla tin-tungsten district, Egypt, 638
Middletown district, Connecticut, 355
ore deposits, Cordillera Real, Bolivia, 597
pegmatites, Grant Co., N. M., 700
Red Rose tungsten mine, Brit. Columbia, 435
Wilbert mine, Idaho, 369
Marble, porosity tests, 61, 76
Martin, H. A., on granite, 96
Martini, H. J., on faults, 717
Maryland, clays, Pennsylvanian (abstract), 420
Mead, W. J., on ore horizons, 57

Meinzer, O. E., *Report on ground water by the Research Committee of the Society of Economic Geologists*, 672–675
on ground water, 673
Meinzer, O. E., *et al.*, on water, 631
Mellor, J. W., on alum, 572
on sodium carbonate, 260
Memorials, Loughlin, G. F., 313
Mercury, geochemistry, 731
Merwin, H. E., on sanidine, 711
*Metalliferous geochemical zones of Australia* (Hills), 478
Metallogenesis, 413, 713, 725
Australia, zones, 478
Cordillera Real region, Bolivia, 595, 605
Metallogenetic provinces, 731
Metallurgy, tungsten (review), 500
Metamorphism, Ajo district, Ariz. (review), 585
Bolivia, Cordillera Real region, 596, 603
coal (report), 512
Red Rose tungsten mine area, B. C., 442
Sangdong tungsten mine, Korea, 473
Sixteen to One vein, Calif., 214
*Metasomatic processes* (Holser), 384
Mexico, copper, Cananea district, 345
Penoles area, limestone, permeability, 73
Meyerhoff, H. A., on Puerto Rico, 564
Mica, 268, 324, 348, 648
muscovite, United States (abstract), 418
Michell, W. D., abstract by, 416
Michigan, ground water, Iron River district (abstract), 410
Mignone, M. L., books received, 589
reviews by, 307, 747, 748
Miholić, S., *Ore deposits and geologic age*, 713–720
on faults, 714
on mineral water, 713
Miller, B. L., and Singewald, J. T., Jr., on Cordillera Real, Bolivia, 598
Miller, W. J., on pegmatites, 710
Minami, E., analyses by, 730
*Mineral deposits of magmatic origin* (Guimarães), 721
Mineral industry, Bolivia (review), 748
Korea (abstract), 427
Mineral resources, Texas (review), 501
*Mineral sulpho salts: XI—Wittichenite (klaprothite), Studies of* (Nuffield), 147
Mineralization, 58, 528
Ajo district, Ariz. (review), 585
Belgian Congo (review), 404
cassiterite, 251
cobalt, Blackbird district, Idaho, 26, 40
copper and alteration facies, 351
Cordillera Real, Bolivia, 609
downward persistence, 547
gold, 397
Kolar field, 94, 115
pipe deposits, Australia, 272
scheelite, Sangdong mine, Korea, 473
tin, Colquiri, Bolivia, 8
*Mineralization—Continued*
tin-tungsten, Igla district, Egypt, 644
tungsten, Boulder, Colo., 53
Yellowknife area, N.W.T., 696
Mineralization and igneous rocks, 539
*Mineralization in the Blackbird district, Lemhi County, Idaho, Cobalt* (Anderson), 22
Mineralogy, beryl pegmatites, Connecticut, 357
dictionary (review), 307
fault zones, Yellowknife, N.W.T., 695
igneous minerals (review), 587
lead-silver ore, Wilbert mine, Idaho, 371
Mesabi Iron Range, Minn. (review), 199
ores, cobalt, Blackbird district, Idaho, 27
Cordillera Real, Bolivia, 596, 609
gold, Sixteen to One vein, Calif., 232
pegmatites, Grant Co., N. M., 704
phosphate deposits, Uganda, 142
pipe deposits, Australia, 273
Red Rose tungsten mine, B. C., 444
Sixteen to One vein, Calif., 211
spectroscopy, minor elements, Red Rose mine, B. C., 460
tin, Colquiri mine, Bolivia, 8
Minerals, identification and analysis (review), 86
*Minerals and Rocks, Report of Committee on Basic Research in the Field of Industrial* (Gillson and Jahns), 737
Mines Register—1946 edition (review), 200
Mining, Bolivia (review), 748
Sangdong tungsten deposit, Korea, 466, 474
Minnesota, iron, Mesabi Range (review), 199
Mississippi, ground water, Mississippi River embayment, 626
*Mississippi River embayment, Groundwater conditions and problems in the upper* (Schneider), 626
Mississippi Valley mineralization, report, 525
Missouri, ground water, Mississippi River embayment, 626
Tri-State district, ore horizons, 74
Mixius, F. K., on faults, 718
Mörner, C. T., analyses by, 716
Mohler, N. M., on quartz, 705
Molecular streaming, 386
Molybdenite, 450, 474
Manchuria, Yang-chia-chang-tzu district (abstract), 426
pipe deposits, Australia, 265
Molybdenum, Manchuria, Yang-chia-chang-tzu district (abstract), 426
Moneymaker, B. C., abstracts by, 411
Moonstone, 703
Morey, G. W., and Burlew, J. S., on silica, 560
Morey, G. W., and Fenner, C. N., on silica, 560

Morey, G. W., and Fleischer, M., on silica, 560
Morey, G. W., and Ingerson, E., on silica, 560
Murdoch, J., on wittichenite, 152
Muscovite, United States (abstract), 418
Muskat, M., on permeability, 62
Mysore, gold, Kolar field, 93

National Research Council, reports on ore deposits, 525
Native bismuth, 265
Native silver, 33, 39
Natural gas, bibliography (review), 588
  Gulf Coast, report (review), 86
  Texas (review), 501
  United States (review), 87
Nelsonite, 195
Němec, B., Babička, J., and Oborský, A., on gold, 577
Netherlands, ground water (review), 680
Nevada, copper, Ely district, 336
  magnesite, Gabbs deposit (abstract), 420
Newhouse, W. H., on crystallization, 78
  on direction of flow, 551
  on ore deposits, 525
  on ores, 248
  on quartz, 648
  on sphalerite, 518
  on structure, 58
New Mexico, *An eolian dam near Tucumcari* (Dobrovolny and Townsend), 492
  *Shallow, high-temperature pegmatites, Grant County* (Kelley and Branson), 699
  *The temperature of crystallization of a fluorite crystal from Luna County* (Twenhofel), 78
  copper, Chino deposit, 332
  fluorspar, Zuni Mtns. (abstract), 417
New York, talc, Gouverneur district (abstract), 419
Niggli, P., on ore deposition, 726
  on ore genesis, 487
Nolan, T. B., on Basin-and-Range Province, 556
Nonmetallic minerals, research, 737
Norman, G. W. H., abstract by, 412
North Carolina, feldspar, pegmatite deposits (abstract), 420
North West Territory, Yellowknife area, structure, 687
Norway, copper and zinc content of plants, 573
Nuffield, E. W., *Studies of mineral sulphosalts: XI—Wittichenite (klaprothite)*, 147–160

Oceans (review), 406
Ocher, Whipstick, New South Wales, 270
Oder, C. L., and Miller, H. W., on dolomite, 541
Odman, O., on Mt. Elgon, Uganda, 137
Oklahoma, Tri-State area, ore horizons, 74
Ontario, Kirkland Lake-Noranda belt (abstract), 428
  Kirkland Lake-Val d'Or break (abstract), 412
Openings, 384
*Ore, Expansion of geophysical methods applicable to* (Beer's), 545
  *Sericite-kaolin alteration as a guide to* (Lovering), 534
Ore bodies, tin, Colquiri district, Bolivia, 18
Ore deposits, Australia, zones, 478
  Belgian Congo (review), 404
  beryl pegmatite types, Conn., 357
  cassiterite, 251
  cobalt, Blackbird district, Idaho, 26
  Colquiri tin district, Bolivia, 13
  concealed, prospecting (abstract), 415
  copper porphyries, alteration types, 349
  genesis (abstract), 413
  hypogene, downward limits, 547
  Kirkland-Lake Val d'Or belt, Ont.-Que. (abstract), 428
  pipes, Australia, 265
  prospecting (abstract), 414
  Sixteen to One vein, Calif., 214
  tin-tungsten, Igla district, Egypt, 644
*Ore deposits and geologic age* (Miholić), 713
*Ore deposits of the eastern Andes of Bolivia. The Cordillera Real* (Turneaure and Welker), 595
*Ore Deposits of the Society of Economic Geologists, Report of the Committee on* (Johnston), 524
*Ore districts, Detailed studies of zoning in* (Blanchard), 543
*Ore horizons, Some physical characteristics of certain favorable and unfavorable* (Rove), 57, 161
*Ore in certain limestone beds, Causes for the selective localization of* (Brown), 535
*Ore in the Kolar gold field, Structural principles controlling the occurrence of* (Bichan), 93
Ore magma, 726
Ore shoots, Cordillera Real, Bolivia, 611
  downward persistence, 549
  gold, Kolar field, 126
  Red Rose tungsten mine, B. C., 454
  Sixteen to One vein, Calif., 230, 240
  tungsten, Sangdong mine, Korea, 471
  Wilbert mine, Idaho, 373
*Ore supply for the future, Iron* (Hotchkiss), 205
*Ore transport, Volcanic emanations as keys to* (Ross), 537
*Ores, The genesis of intrusive magnetite and related* (Shand), 634
  gold, Sixteen to One vein, Calif., 232

*Ores—Continued*
lead-silver sulfosalts, Clark Fork, Idaho, 305
tin, Colquiri mine, Bolivia, 13
tungsten, Sangdong deposit, Korea, 470
*Origin, Mineral deposits of magmatic* (Guimarães), 721
cobalt-gold ore, Blackbird district, Idaho, 41
craters (review), 747
ores, Cordillera Real, Bolivia, 605, 618
tin, Colquiri district, Bolivia, 19
tungsten, Red Rose mine, B. C., 454
Wilbert mine, Idaho, 381
pegmatites, 699, 706
phosphate deposits, Uganda, 146
Sixteen to One vein, Calif., 218
talc, Gouverneur district, N. Y. (abstract), 419
tungsten veins, Boulder, Colo., 53
Orphaned pipe deposits, 270, 276
Orthoclasation, 585
Orthoclase, 337, 347, 446
Overstreet, W. C., abstract by, 424
Oxidation, Colquiri tin mine, Bolivia, 13
Red Rose tungsten mine area, B. C., 450

Palache, C., Berman, H., and Frondel, C., on pyrite lattice, 394
Paragenesis, alteration minerals, Sixteen-to-One vein, Calif., 223
copper porphyry alteration minerals, 346
gold, 397
metallurgical interpretation (abstract), 413
ores, cobalt, Blackbird district, Idaho, 27
gold, Kolar field, 117
scheelite, Boulder, Colo., 52
tin Colquiri mine, Bolivia, 9
tin-tungsten, Igla district, Egypt, 640, 664
tungsten, Red Rose mine, B. C., 450
pegmatites, Grant Co., N. M., 706
sericite-kaolin alteration, 535
Park, C. F., on dolomite, 541
Parkinson, G. A., and Barnes, V. E., grinding pebbles, Texas (review), 501
Peck, L. C., analysis by, 342
Pegmatites, 727
*Grant County, New Mexico, Shallow, high-temperature* (Kelley and Branson), 699
beryl, Connecticut, 353
Chile, magnetite deposits (abstract), 417
Cordillera Real, Bolivia, 609
Kolar gold field, Hindustan, 93
research, 742
zoning and prospecting (abstract), 420
Pegmatites and pipe deposits, Australia, 285
Pehrson, E., on iron ore, 207
Penemineralized carbonates, 541
Pennebaker, E. N., on Ely district, Nev., 336
Pennsylvania, zinc, Friedensville slime ponds, 575
Permeability *vs.* porosity, 60
Perrin, R., and Roubault, M., on subcapillary openings, 390
Perry, V. D., on Cananea district, Mexico, 345
Perutz, M. F., on colloids (review), 749
Petersen, T., on copper, 154
on klaprothite, 154
Peterson, N. P., Gilbert, C. M., and Quick, G. L., on alteration, 320, 328
Petrascheck, W., on cassiterite, 288
Petroleum, 199, 748
*Society of Economic Geologists, Report of the Committee of Research on* (Heald), 676
bibliography (review), 588
continental shelf possibilities (editorial), 83
Gulf Coast, report (review), 86
production by water (review), 679
Texas (review), 501
United States, report (review), 87
Venezuela and Trinidad (review), 588
Phillips, A. H., and Hess, H. H., on carbonatization, 223
Phillips, F. C., on sulphide minerals, 157
on wittichenite, 148
Phlogopite, 139
*Phosphate deposits of the eastern province, Uganda* (Davies), 137
Phosphates, Jap mandated islands (abstract), 425
Photomicrographs—
alteration in porphyry copper, 333
cassiterite, synthetic, 259
ores, gold, Kolar field, 120
Red Rose tungsten mine, B. C., 446
scheelite, Boulder, Colo., 49
tin, Colquiri, Bolivia, 10
ores and rocks, Blackbird district, Idaho, 28
Igla district, Egypt, 647
Sixteen to One vein, Calif., 217
Wilbert mine, Idaho, 379
*Physical characteristics of certain favorable and unfavorable ore horizons, Some* (Rove), 57, 161
Physiography (review), 307
Pilger, A., on faults, 715
Pilz, R., and Donath, M., on the Cordillera Real, Bolivia, 598
*Pipe deposits of eastern Australia, Some* (Blanchard), 265
Placers, gold, Chile, Tierra del Fuego (abstract), 418
Plans—
Bordonaro beryl pegmatite, Connecticut, 359
Doble Ancho level, Colquiri, Bolivia, 7
Mysore mine, Kolar gold field, 107
pipe deposits, Australia, 279

*Plans—Continued*
Sangdong tungsten mine, Korea, 472
Wilbert mine, Idaho, 372
*Plants on the Friedensville zinc slime ponds in relation to biogeochemical prospecting, The zinc content of* (Robinson, Lakin and Reichen), 572
Platinum, Brazil, Morro do Pilar deposit, 735
Plummer, F. B., water supplies, Texas (review), 501
Poisseuille's equation, 386, 390
Poisson's ratio, 174
Poljak, J., on faults, 714
Pollution of ground water, 675
Porosity *vs.* permeability, 60
*"Porphyry Copper" deposits, Hydrothermal alteration in the* (Schwartz), 319
Pratt, W. E., editorial by, 83
*Prospecting, The zinc content of plants on the Friedensville zinc slime ponds in relation to biogeochemical* (Robinson, Lakin, and Reichen), 572
geochemistry methods (abstract), 414
Pryor, T., on folds, 112
Pseudomorphs, 393
allophane after feldspar, 340
*Puerto Rico, Geology and ground-water resources of* (McGuinness), 563
ground water (abstract), 409
Pulfrey, W., on igneous rocks, 137
Pyrite, 11, 94, 234, 320, 340, 394
*Pyrite geo-thermometer* (Smith), 515
Pyritization, 378
Pyrrhotite, 39, 294

Quartz, 29, 94, 112, 217, 225, 233, 268, 323, 399, 446, 471, 560, 609, 618, 645, 703
*Quartz vein, Alleghany, California, The original Sixteen to One gold* (Cooke), 211
Quebec, Kirkland-Val d'Or break (abstract), 412
Noranda-Val d'Or belt (abstract), 428

Radioactivity of earth's crust, 719
Ragweed, zinc content, Pa., 574, 577
Ransome, F. L., on Bisbee area, Ariz., 69
on Miami district, Ariz., 329
on porphyry, 344
on Ray district, Ariz., 331
Ransome, F. L., and Calkins, F. C., on carbonatization, 541
Rare earths, occurrence in sediments, 730
Rastall, R. H., on carbonates, 540
on wolframite, 288
Rastall, R. H., and Wilcockson, W. H., on tactite, 474
Reagen, P. H., on Chojlla district, Bolivia, 603
*Red Rose tungsten mine, Hazelton, British Columbia, Geology of the* (Stevenson), 433
Redfield, R. C., lead-silver, Texas (review), 501
Reichen, L. E., Robinson, W. O., with Lakin, H. W., *The zinc content of plants on the Friedensville zinc slime ponds in relation to biogeochemical prospecting*, 572–582
Reid, J. R., on a tectonic line, 481
Reid, W. T., abstract by, 428
Replacement, gouge by scheelite, Boulder, Colo., 51
research, 528
Replacement processes, 384
*Report of Committee on Basic Research in the Field of Industrial Minerals and Rocks* (Gillson and Jahns), 737
*Report of the Committee on Research on Ore Deposits of the Society of Economic Geologists* (Johnston), 524
*Report of the Committee on Research on Petroleum, Society of Economic Geologists* (Heald), 676
*Report on ground water by the Research Committee of the Society of Economic Geologists* (Meinzer), 672
Research Committee, report, 505
*Research in the Field of Industrial Minerals and Rocks, Report of Committee on Basic* (Gillson and Jahns), 737
*Reviews—*
Ajo mining district, Arizona (Gilluly), Butler, 583
Coal reserves of Canada, Report of Royal Commission on Coal and Maps (Mackay), 679
Concise chemical and technical dictionary (Bennett), 307
Le Congo physique (Robert), 404
Ducktown, back in Raht's time (Barclay), 87
Elements of engineering geology (Ries and Watson), 406
Elements of soil conservation (Bennett), 307
Fundamentals of earth science (Thompson), 405
Geologia de Bolivia (Ahlfeld), 86
Geology and ground-water resources of the Island of Hawaii (Stearns and MacDonald), Cederstrom, 498
Geology of Venezuela and Trinidad, 2nd edit. (Liddle), 588
Identification and qualitative chemical analysis of minerals (Smith), 86
Igneous minerals and rocks (Wahlstrom), 587
Memorandum sobre los problemas de la industria minera de Bolivia (memorandum on the problems of the Bolivian mining industry) (Aramayo), Mignone, 748
Mineralogy and geology of the Mesabi Range (Gruner), Jones, 199
Minerals Yearbook, 1945 (Keiser), 588

*Reviews—Continued*
Oil and gas field development in the United States (Sinclair), 87
Oil for victory, the story of petroleum in war and peace, 199
Origin and development of craters (Jaggar), Mignone, 747
Petroleum Production. Vol. III. Oil production by water (Jones), 679
Principes de Géomorphologie Normale (principles of normal geomorphology) (Macar), 307
Recent ground water investigations in the Netherlands (Krul and Liefrinck), 680
Regions and nations of the world (Lackey and Anderson), 87
Review of petroleum geology in 1946 (Van Tuyl *et al.*), 588
Texas mineral resources, 501
This great and wide sea (Coker), 406
Tungsten, its history, geology, ore-dressing, metallurgy, chemistry, analysis, applications, and economics (Li and Wang), 500
When the earth quakes (Macelwane), 680
When the oil wells run dry (Fuchs), 748
Yanqui in Patagonia (Willis), 501
1945 reference report on certain oil and gas fields of North Louisiana, South Arkansas, Mississippi, and Alabama (Shreveport, La., Geol. Soc.), 86
Ribbon quartz, 226
Rideal, E. K., review of book edited by, 749
Ries, H., and Watson, T. L., review of book by, 406
Robert, M., review of book by, 404
Roberts, G. D., abstract by, 410
Roberts, R. J., on tactite, 474
Robinson, W. O., and Edgington, G., on rare earths, 580
Robinson, W. O., Lakin, H. W., and Reichen, L. E., *The zinc content of plants on the Friedensville zinc slime ponds in relation to biogeochemical prospecting*, 572–582
*Rocks, Comparison between "productive" and "barren" igneous* (Buddington), 539
*Report of Committee on Basic Research in the Field of Industrial Minerals and* (Gillson and Jahns), 737
Ajo district, Ariz. (review), 583
crushing tests, 176
igneous rocks (review), 587
rupture theories, 166
spectroscopy, Red Rose mine, B. C., 461
Rodgers, J., abstract by, 425
Rogers, A. F., on klaprothite, 156
Rolker, C. M., on veins, 104
Ross, C. P., on Dome district, Idaho, 368
Ross, C. S., *Volcanic emanations as keys to ore transport*, 537–539
discussion by, 194
on titanium, 194
Rove, O. N., *Some physical characteristics of certain favorable and unfavorable ore horizons*, 57–77, 161–193
Rumbold, W. R., on Cordillera Real region, Bolivia, 598
Rupture of rocks, 166
Russell, W. L., on rock cubes, 60
Rutile, 194

Sales, R. H., on bottoming of ores, 553
on faults, 178
Salt domes, Gulf Coast, report (review), 86
Salt flowage, research, 678
Samec, M., and Guzelj, L., analysis by, 715
Samoyloff, V., on tin, 251
Sampling, beryl pegmatites, Conn., 365
ore horizons, 59
Sandberger, F., on klaprothite, 154
Sandell, E. B., and Goldich, S. S., on lead, 463
*Sangdong tungsten deposit, southern Korea* (Klepper), 465
Sanidine, 699, 703
Schaller, W. T., on pegmatites, 709
on tin, 251
Scheelite, 445, 465, 470
*Scheelite in the Boulder district, Colorado* (Tweto), 47
Schenck, R., on copper, 157
Schmedeman, O. C., on ore fluids, 667
Schmitt, H., on Hanover area, N. M., 71
Schneider, R., *Ground-water conditions and problems in the upper Mississippi River embayment*, 626–633
Schneider, R., on copper, 154
on wittichenite, 154
Schneiderhöhn, H., and Ramdohr, P., on klaprothite, 156
on minerals, 305
Schottky, W., on lattice sites, 391
Schouten, E. S., on subcapillary openings, 389
Schulman, J. H., on emulsions (review), 749
Schwartz, G. M., *Hydrothermal alteration in the "Porphyry Copper" deposits*, 319–352
on alteration, 321
*Scientific notes and news*, 91, 203, 317, 433, 513, 593, 684, 753
Sections—
beryl pegmatites, Connecticut, 360
Colquiri district, Bolivia, 6
Mississippi River embayment, 628
pipe deposits, Australia, 268
Principal and San Antonio veins, Cordillera Real, Bolivia, 612
Red Rose tungsten mine area, B. C., 438

*Sections—Continued*
Sangdong tungsten mine, Korea, 472
Sixteen to One vein, Calif., 215
veins, Kolar gold field, 102
Wilbert mine, Idaho, 374
Sedimentation, coal formation (report), 511
petroleum formation (editorial), 83
Sediments, geochemistry, 729
phosphates, Jap mandated islands (abstract), 425
research, 677, 743
sulphur, Japan (abstract), 425
Seidel, G., on faults, 718
Seidl, K., on carbonates, 540
Seismology, earthquakes (review), 680
Selb,—., on copper, 154
Selenium, plant indicators, 574
Sellards, E. H., industrial minerals, Texas (review), 501
Sellards, E. H., and Evans, G. L., mineral resources, Texas (review), 501
Sellards, E. H., and Hendricks, L., oil and gas, Texas (review), 501
Semseyite, 305
Sericite, 53, 332, 348
*Sercite-kaolin alteration as a guide to ore* (Lovering), 534
Sericitization, 378, 451, 454, 463
Serpentine, 212
Serpentinite, 212
Serpentinization, 216
Shainin, V. E., abstracts by, 417, 418
Shainin, V. E., with Cameron, E. N., *The beryl resources of Connecticut*, 353–367
Shand, S. J., *The genesis of intrusive magnetite and related ores*, 634–636
on igneous rocks, 138
on magma, 146
on water, 724
Shepherd, S. R. L., on molybdenite, 275
Sheppard, M., on grindability, 184
Shimer, J. A., on minerals, 460
Shiraki, T., on Sangdong area, Korea, 468
Short, M. N., on wittichenite, 152
Shreveport, La., Geol. Society, oil and gas report (review), 86
Siderite, 10, 39
*Silica, Transportation and deposition of* (Ingerson), 560
Silicates, 721
Silicification, 216, 329, 377, 451
Silver, Ajo district, Ariz. (review), 583
Bolivia, Cordillera Real region, 596
mining (review), 748
Colorado, Alma district, mineralization, 68
Colquiri tin mine, Bolivia, 2
gold-silver ratios, 402
Korea, Ongjin-Haeju deposit (abstract), 422
sulfosalts, Clark Fork, Idaho, 305
Texas, Mica and Bird mine (review), 501
*Silver—Continued*
Wilbert mine, Idaho, 368
Simmons, W. C., on tin, 251
Sinclair, W. G., review of book edited by, 87
Singewald, J. T., Jr., on cassiterite, 288
on Chojlla district, Bolivia, 603
on chromite, 572
on tin, 251
Singewald, Q. D., abstract by, 421
Singewald, Q. D., and Butler, B. S., on limestone, 68
*Sixteen to One gold-quartz vein, Alleghany, California, The original* (Cooke), 211
Slichter, L. B., and Telkes, M., on pyrite, 518
Smeeth, W. F., on gneiss, 95
Smekal, A., on crystals, 390
Smith, F. G., *The pyrite geo-thermometer*, 515–523
*Transport and deposition of the non-sulphide vein materials. II. Cassiterite*, 251–264
on colloidal transportation, 669
on pyrite, 515
Smith, G., on direction of flow, 551
Smith, O. C., review of book by, 86
Smith, R. R., on vinyl polymerization (review), 749
Smith, W. C., and Guild, P. W., on tactite, 474
Smulikowski, K., and Kozlowski, R., on the Cordillera Real, Bolivia, 598
*Society of Economic Geologists, Report of the Committee on Research on Ore Deposits of the* (Johnston), 524
*Report of the Committee on Research on Petroleum* (Heald), 676
*Report on ground water by the Research Committee of the* (Meinzer), 672
Soils, Belgian Congo (review), 405
conservation (review), 307
moisture research, 674
Solid phase reactions, 392
Solid solution, 721
Sorby, H. C., on crystallization, 78
Spectroscopy, gold, Sixteen to One vein, Calif., 249
ores and rocks, Red Rose mine, B. C., 455
Spencer, A. C., on Ely district, Nev., 336
on magnetite, 634
Spencer, A. C., and Paige, S., on Hanover area, N. M., 71
on Santa Rita district, N. Mex., 332
Spessartite, 270
Sphalerite, 11, 39, 238, 417, 523
Springs, Hawaii (review), 499
metal content of waters, 713
Spurr, J. E., on molybdenite, 288
on ore horizons, 178
Stannite, 302

Stearns, H. T., and MacDonald, G. A., review of bulletin by, 498
Steinmann, G., on folding, 603
on tuffs, Bolivia, 602
Stenzel, H. B., coal output, Texas (review), 501
faults, Houston Co., Texas (review), 501
Stevenson, J. S., *Geology of the Red Rose tungsten mine, Hazelton, British Columbia*, 433–464
on tungsten, 437
Stibnite, 618
Stille, H., on faults, 718
Stočes, B., and White, C. H., on ore horizons, 178
Stock piles, U. S., 205
Stocks, Basin-and-Range Province, 557
Stoiber, R. E., on direction of mineralization, 551
Stratigraphy, Ajo district, Ariz. (review), 583
Blackbird district, Idaho, 24
Colquiri tin district, Bolivia, 3
Cordillera Real, Bolivia, 598
Dome district, Idaho, 370
Mississippi River embayment, 629
Puerto Rico (abstract), 409
Sangdong tungsten deposit, Korea, 468
Tucumcari district, N. Mex., 494
Venezuela and Trinidad (review), 588
*Structural control and wall-rock alteration at the Wilbert mine, Dome district, Butte County, Idaho* (Anderson) 368
*Structural features of the Yellowknife area, Regional* (Campbell), 687
*Structural principles controlling the occurrence of ore in the Kolar gold field* (Bichan), 93
Structure, Ajo district, Ariz. (review), 584
Blackbird district, Idaho, 25
Colquiri district, Bolivia, 5
Cordillera Real, Bolivia, 604
fluorspar deposits, Zuni Mtns., N. Mex. (abstract), 417
ground-water relations, 675
Kirkland Lake-Val d'Or belt, Ont.-Que. (abstract), 428
Quebec, Kirkland-Val d'Or break (abstract), 412
Red Rose tungsten mine area, B. C., 442, 452
Sangdong tungsten deposit, Korea, 468
Sixteen to One vein, Calif., 229
Wilbert mining area, Idaho, 370
*Structures, Emplacement of igneous rocks in relation to favorable* (Hulin), 558
Stylolites and mineralization, 67, 75
Suess, E., on Rhine Valley, 718
Sullivan, J. D., Keck, W. E., and Oldright, G. L., on ore horizons, 57
Sulphides, Colquiri tin mine, Bolivia, 8
*Sulpho-salts: XI—Wittichenite (klaprothite), Studies of mineral* (Nuffield), 147
Sulphur, Japan (abstract), 425
Sutherland, G. B., on colloids (review), 749
Sweden, mineral waters, analyses, 716
Swinnerton, A. C., on quartz, 561
Synthesis, quartz crystals, 561

Tables, beryl pegmatites, Connecticut, 358
cassiterite, transport and deposition tests, 255
chemical analyses, mineral waters, Yugoslavia, 715
phosphate minerals, Uganda, 143
rocks, granodiorites, B. C., 440
zinc in soils and vegetation, 575
mineral production, pipe deposits, Australia, 280
minerals, rims and fences, 236
ore deposits, Nat. Res. Council reports, 525
ore horizons, physical properties, 67, 168
quartz, inversion temperature at depths, 117
research in nonmetallic minerals, 741
stratigraphy, Mississippi River embayment, 630
Sangdong tungsten deposit, Korea, 468
sediments, Tucumcari district, N. Mexico, 495
veins, dip and strike, Cordillera Real, Bolivia, 607
voids in silicates, 723
wittichenite, 149
Tacsite, 474
Talc, New York, Gouverneur district (abstract), 419
research, 743
Tantalite, 733
Tantalum, Australia, 487
Taylor, N. W., solid phase reactions, 392
Taylor, N. W., and Williams, F. J., on solid phase reactions, 392
Technique, cassiterite, transport and deposition, 254
identification igneous rocks and minerals (review), 587
minerals, analysis and identification, 86
permeability testing, 61
pyrite geothermometer, 518
temperature of crystallization determination, 78
x-ray *vs.* etching tests of ores, 305
*Temperature of crystallization of a fluorite crystal from Luna County, New Mexico* (Twenhofel), 78
Tennessee, copper, Ducktown district, history (review), 87
ground water, Mississippi River embayment, 626

Tennessee Valley Authority, engineering geology (abstract), 411
mineral investigations (abstract), 411
Tenney, J. B., on Bisbee area, Ariz., 69
*Tensional dilation, The ubiquity of gold values and their relation to zones of* (Bichan), 396
Tetrahedrite, 234
Texas, fluorspar, Spar valley (abstract), 416
mineral resources (review), 501
Shafter area, limestones, permeability, 73
Theis, C. V., and Stuart, W. T., abstract by, 410
Thermometer, pyrite, 515
Thomas, H. H., and Bailey, E. B., on magmas, 728
Thompson, H. D., review of book by, 405
Thomson, J. E., abstract by, 412
Tin, Belgian Congo (review), 404
Bolivia, Cordillera Real region, 595, 605, 609
mining (review), 748
cassiterite, 251
pipe deposits, Australia, 265
*Tin mine, Bolivia, Geology of the Colquiri* (Campbell), 1
*Tin-tungsten deposit in Egypt* (Amin), 637
Titanium, Virginia (discussion), 194
Tolman, C. F., on turbulence, 394
Topaz, 650
Tourmaline, 26, 116, 603, 651
Townsend, R. C., with Dobrovolny, E., *An eolian dam near Tucumcari, New Mexico*, 492–497
*Transport and deposition of the non-sulphide vein materials. II. Cassiterite* (Smith), 251
*Transportation and deposition of silica* (Ingerson), 560
Tree leaves, zinc content, Pa., 576
Tremolite, 419
Trinidad, geology (review), 588
Tri-State area, ore horizons, permeability tests, 74
Trough of veins, 228
Tuckett, R. F., on elasticity (review), 749
*Tucumcari, New Mexico, An eolian dam near* (Dobrovolny and Townsend), 492
Tungsten (review), 500
Bolivia, Cordillera Real region, 595, 605, 609
mining (review), 748
Japan and Korea (abstract), 421
scheelite, Boulder, Colorado, 47
*Tungsten deposit, southern Korea, The Sangdong* (Klepper), 465
*Tungsten deposit in Egypt, Tin* (Amin), 637
*Tungsten mine, Hazelton, British Columbia, Geology of the Red Rose* (Stevenson), 433
Tungstite, 450
Turneaure, F. S., on tin, 596
Turneaure, F. S., and Gibson, R., on metals, 596
Turneaure, F. S., and Welker, K. K., *The ore deposits of the eastern Andes of Bolivia. The Cordillera Real*, 595–625
Tuttle, O. F., and Twenhofel, W. S., on crystals, 516
Twelvetrees, W. H., and Ward, L. K., on cassiterite, 288
Twenhofel, W. S., *The temperature of crystallization of a fluorite crystal from Luna County, New Mexico*, 78–82
Tweto, O., *Scheelite in the Boulder district, Colorado*, 47–56
on scheelite, 445

*Uganda, Phosphate deposits of the eastern province* (Davies), 137
Umpleby, J. B., on cobalt, 22
on galena, 371
Underground water, Belgian Congo (review), 405
Hawaii (review), 498
Kentucky, limestone, solutional effects (abstract), 409
metal content of spring water, 713
Michigan, Iron River district (abstract), 410
Netherlands (review), 680
Puerto Rico (abstract), 409
Tucumcari district, N. Mex., 495
United States, copper porphyry deposits, 319
iron ore supply, 205
Minerals Yearbook (review), 588
muscovite (abstract), 418
oil and gas, report (review), 87
phosphates, Jap mandated islands (abstract), 425
U. S. Geol. Survey, geochemical prospecting (abstract), 414
Uranium, Belgian Congo (review), 404
mineral water content, Yugoslavia, 713
Urry, W. D., on radium, 719
Uspensky, N. M., on micropegmatite, 664
Utah, copper, Bingham district, 325

Van Hise, C. R., on openings, 384
Van Tuyl, F. M., *et al.*, review of bibliography by, 588
Van Wagenen, H. R., on scheelite, 47
Vei, C. J., on molybdenite, 287
*Vein, Alleghany, California, The original Sixteen to One gold-quartz* (Cooke), 211
*Vein materials. II. Cassiterite. Transport and deposition of the non-sulphide* (Smith), 251

Veins, 732
cobalt-gold, Blackbird district, Idaho, 26
Cordillera Real region, Bolivia, 596, 605
fluorspar, Zuni Mtns., N. Mex. (abstract), 417
fracturing and gold deposition, 398
gold, Kolar field, 101
Sangdong tungsten area, Korea, 474
scheelite, Boulder, Colo., 47, 50
Red Rose mine, B. C., 444
tin, Colquiri district, Bolivia, 5
tin-tungsten, Igla area, Egypt, 644
tungsten, Sangdong deposit, Korea, 466
zoning (abstract), 414
Venezuela, geology (review), 588
Violets, zinc content, Pa., 573, 576
Virginia, Austinville area, permeability tests, 74
titanium (discussion), 194
Vitaliano, C. J., and Callaghan, E., abstract by, 420
Vogt, J. H. L., on halides, 251
Vogt, T., Braadlie, D., and Bergh, H., on copper and zinc, 573
*Volcanic emanations as keys to ore transport* (Ross), 537
Volcanism, Hawaii (reviews), 498, 747
Volcanoes, craters (review), 747
Vugs, 272
formation temperature, 522
scheelite, Boulder, Colo., 50

Waage, K. M., abstract by, 420
Wade, M. L., on cassiterite, 294
Wagner, C., on solid phase reactions, 392
Wahlstrom, E. E., review of book by, 587
*Wall-rock alteration at the Wilbert mine, Dome district, Butte County, Idaho, Structural control and* (Anderson), 368
Warren, C. H., on pegmatites, 710
Warren, L. E., manganese and dolomite, Texas (review), 501
Washington, H. S., on granodiorite, 440
Watanabe, M., on diffusion, 387
Water, petroleum production relations (review), 679
Weathering, Ajo district, Ariz. (review), 585
Welker, K. K., with Turneaure, F. S., *The ore deposits of the eastern Andes of Bolivia. The Cordillera Real,* 595–625
Wells, logging research, 678
Puerto Rico, 571
White, C. H., on ore fluids, 666
Whitman, A. R., on diffusion, 387
Wiese, J. H., and Cardenas, D., on tactite, 474
*Wilbert mine, Dome district, Butte County, Idaho, Structural control and wall-rock alteration at the* (Anderson), 368
Will, H., analyses by, 717
Williams, D., on minerals, 718
Willis, B., review of book by, 501
Wilmot, V. E., on tungsten, 434
Wilson, E. D., on Basin- and Range Province, 556
Wilson, M. E., abstract by, 412
Wilstatter, R., and Stoll, A., on zinc, 581
Winchell, A. N., on mica, 646
Winkler, A., on Alpine System, 714
Withey, M. O., and Aston, J., on strength of cylinders, 162
*Wittichenite (klaprothite), Studies of mineral sulpho-salts: XI*—(Nuffield), 147
Wolframite, 474, 648
pipe deposits, Australia, 266
Wright, C. W., on stibnite, 618
Wright, F. E., and Larsen, E. S., on quartz, 711
Wright, L. B., on solutions, 58
Wyckoff, R. D., *et al.*, on permeability, 62
Wyckoff, R. W., on minerals, 461

X-ray patterns, cassiterite, 261
X-ray study, sulfosalts in ores, 305
wittichenite, 148

*Yellowknife area, Regional structural features of the* (Campbell), 687
Yugoslavia, metals in mineral waters, 713

Zawadski, J., and Bretsznajder, S., on solid phase reactions, 392
Zies, E. G., on hydrogen sulphide, 19
Zinc, Chile, Batuco deposit (abstract), 417
Cordillera Real, Bolivia, 610
geochemistry, 730
Ongjin-Haeju deposit, Korea (abstract), 422
pipe deposits, Australia, 265
Quebec, Kirkland-Val d'Or break (abstract), 412
Noranda-Val d'Or belt (abstract), 428
Tri-State district, ore horizons, 74
*Zinc content of plants on the Friedensville zinc slime ponds in relation to biogeochemical prospecting* (Robinson, Lakin, and Reichen), 572
Zisman, W. A., on Poisson's ratio, 174
Zoisite, 29
*Zones of Australia, The metalliferous geochemical* (Hills), 478
*Zones of tensional dilation, The ubiquity of gold values and their relation to* (Bichan), 396
Zoning 559
Cordillera Real region, Bolivia, 596, 605, 614, 623
feldspar pegmatites (abstract), 420
hypothermal zone, 288
Igla district, Egypt, 666
pegmatites, 709
Connecticut, 354
pipe deposits, Australia, 272
temperature zoning of minerals, 82
*Zoning in ore districts, Detailed studies of* (Blanchard), 543

C15